

Title	Designing wearable sensors for Preventative Health: An exploration of material, form and function
Type	Thesis
URL	http://ualresearchonline.arts.ac.uk/9077/
Date	2015
Citation	Prahl, Anne (2015) Designing wearable sensors for Preventative Health: An exploration of material, form and function. PhD thesis, University of the Arts London.
Creators	Prahl, Anne

Usage Guidelines

Please refer to usage guidelines at <http://ualresearchonline.arts.ac.uk/policies.html> or alternatively contact ualresearchonline@arts.ac.uk.

License: Creative Commons Attribution Non-commercial No Derivatives

Unless otherwise stated, copyright owned by the author

Designing wearable sensors for Preventative Health:
An exploration of material, form and function

Anne Prah

Thesis submitted in partial fulfilment of the requirements
for the degree of Doctor of Philosophy

University of the Arts London
London College of Fashion

September 2015

Abstract

Designing wearable sensors for Preventative Health:

An exploration of material, form & function

The financial burden on global healthcare systems has reached unprecedented levels and as a result, attention has been shifting from the traditional approach of disease management and treatment towards prevention (Swan, 2012). Wearable devices for Preventative Health have become a focus for innovation across academia and industry, thus this thesis explores the design of wearable biochemical and environmental sensors, which can provide users with an early warning, detection and monitoring system that could integrate easily into their existing lives.

The research aims to generate new practical knowledge for the design and development of wearable sensors and, motivated by the identification of compelling design opportunities, merges three strands of enquiry. The research methodology supports this investigation into material, form and function through the use of key practice-based methods, which include Participatory Action Research (active immersion and participation in a particular community and user workshops) and the generation and evaluation of a diverse range of artefacts.

Based on the user-centred investigation of the use case for biochemical and environmental sensing, the final collection of artefacts demonstrates a diverse range of concepts, which present biodegradable and recyclable nonwoven material substrates for the use in non-integrated sensors. These sensors can be skin-worn, body-worn or clothing-attached for in-situ detection and monitoring of both *internal* (from the wearer) and *external* (from the environment) stimuli.

The research proposes that in order to engage a broad section of the population in a preventative lifestyle to significantly reduce the pressure on global healthcare systems, wearable sensors need to be designed so they can appeal to as many users as possible and integrate easily into their existing lifestyles, routines and outfits. The thesis argues that this objective could be achieved through the design and development of end-of-life considered and cost-effective substrate materials, non-integrated wearable form factors and meticulous consideration of a divergent range of user needs and preferences, during the early stages of design practice.

Acknowledgements

I would like to thank my supervisory team at London College of Fashion, University of the Arts London; Professor Sandy Black for providing the opportunity to undertake this PhD research in the first place and her ongoing encouragement, advice and invaluable feedback during the various stages of scoping, developing, undertaking, evaluating and writing-up the research and Professor Ian King for offering additional support and motivation during the writing-up stage of the thesis.

I greatly appreciate the receipt of an EPSRC Creative Industries Knowledge Transfer Network Studentship, a full-time studentship under the Industrial CASE award scheme, funded by the Engineering and Physical Science Research Council (EPSRC). This doctoral award enabled me to dedicate 3.5 years to the project, in order to investigate a fascinating and emerging subject, while further exploring my role as a designer.

Thank you to the London Quantified Self Meetup group for welcoming me into their community and consequently inspiring one of the key aspects of my research practice and both my QSer and user groups, who gave their valuable time, active engagement and feedback during the workshops, which enriched my design practice enormously.

Finally I would like to thank my husband Luke and my friends and family for tolerating my distraction from 'real life' for so long, asking enough but not too many questions about the project (and its completion) and putting up with my disappearance into the research den for months on end to write the thesis. Thank you also to my yoga teachers and fellow yogis, who kept me bendy, focused and motivated during the long writing process.

Table of Contents

Abstract	3
Acknowledgements	4
Definitions of key terms	11
<u>Chapter 1: Introduction</u>	14
1.1 Research Motivation	16
1.2 Format and role of practice	17
1.3 Project aims & objectives	18
1.4 Research Methodology summary	20
1.5 Research questions and proposition	21
1.6 Scope and limitations	23
1.7 Thesis overview	25
<u>Chapter 2: Investigating wearable sensors</u>	28
2.1 Electronic wearable sensors	30
Degrees of sensor integration	
2.1.1 Wearable sensors: Textiles as the sensor carrier	33
Construction	
Surface treatment	
Electronic sensing networks	
2.1.2 Wearable sensors: Clothing as the sensor carrier	43
Garment-specific integration	
Removable/ flexible attachment	
2.1.3 Wearable sensors: Body or skin as the sensor carrier	48
Body-worn	
Skin-worn	
2.1.4 Emerging and future material substrates	50
Flexible & plastic electronics	
Paper electronics & sensors	
2.1.5 Sensing applications for Wearable Technology	54
Lifestyle & fashion	
Sport & fitness	
Health & wellbeing	

Healthcare & medical	
Military, space & industrial	
2.2 Non-electronic wearable sensors	68
2.2.1 Fashion & sportswear textiles	69
Colour & pattern change	
2.2.2 Diagnostics	71
Colour change	
Fluid collection	
2.3 Summary and conclusion	73
<u>Chapter 3: Design opportunities for wearable sensors</u>	75
3.1 Designing for Preventative Health	76
3.1.1 Biochemical sensing	77
3.1.2 Environmental sensing	79
3.2 Designing for the product's end-of-life	81
3.3 Designing non-integrated wearable sensors	85
3.4 Designing for a real user need	88
3.5 Summary and conclusion	92
<u>Chapter 4: Research design and methodology</u>	94
4.1 Significance of practice	95
4.2 Research process	97
4.2.1 Three-stranded enquiry	100
4.2.2 Data collection, generation and evaluation	102
4.3 Research methods and tools	104
4.3.1 Key practice-based methods: Participatory Action Research (PAR)	106
User research & community immersion	
Self-tracking experiment (active participation)	
User workshops	
4.3.2 Key practice-based methods: Artefacts	113
Final collection of artefacts (wearable sensor collections)	
Exploratory artefacts	
4.4 Summary and conclusion	117

<u>Chapter 5: Exploratory sampling</u>	119
5.1 Prototype creation for Smart Fabrics 2013	119
5.2 Additional sampling	125
5.3 Conclusion	134
<u>Chapter 6: Material substrates for wearable sensors</u>	135
6.1 Material driven end-of-life solutions	136
6.2 Closed-loop design approach	139
6.3 Designing material concepts	141
6.3.1 <i>Skin-tech</i>	142
6.3.2 <i>Tecrochet</i>	148
6.3.3 <i>Material concepts evaluation</i>	151
6.4 Additional material research & sampling	153
6.4.1 <i>Wearable substrates overview</i>	153
Rubber-like	
Textile-like	
Paper and film-like	
6.4.2 <i>User workshop 2: Material focus</i>	157
6.4.3 <i>Exploring paper substrates</i>	160
Papermaking	
Wear testing	
6.5 Nonwoven materials: Rubber-like, paper-like and felt-like	166
6.6 Conclusion	169
<u>Chapter 7: Exploring form factors for wearable sensors</u>	171
Preliminary testing of wearable devices	
7.1 Design for in-situ sensing & monitoring	176
7.1.1 <i>Stimuli locations as design inspiration</i>	177
Internal stimuli	
External stimuli	
7.1.2 <i>Designing with on-body locations in mind</i>	182
On-body locations: Internal stimuli	
On-body locations: External stimuli	
Adhesive	

7.2 Form factor design concepts	188
7.2.1 On-body wearable sensor concepts	188
7.2.2 User workshop 2: Form focus	193
7.2.3 User workshop outcomes	196
7.3 Non-integrated wearable sensors: Skin, body and clothing as sensor carriers	198
7.4 Conclusion	199

Chapter 8: Examining function through user-centred design **201**

8.1 Researching user needs: Quantified Self	203
8.1.1 Self-tracking experiment	205
8.2 Connecting with users & communities	209
8.2.1 QS Show & Tell talk 1	210
Event and outcomes 1	
8.2.2 QS Show & Tell talk 2	212
Event and outcomes 2	
8.2.3 QSer workshop (workshop 1)	214
Planning & preparation	
Workshop event	
Workshop outcomes & evaluation	
8.3 Wearable sensors: Blending into users' lives	223
8.4 Conclusion	225

Chapter 9: Design brief creation **227**

9.1 Design brief development	228
9.1.1 User types	229
9.1.2 Artefact criteria	233
9.2 Design brief: User type concepts	235
Techno_ <i>PHILE</i>	
Techno_ <i>ISTA</i>	
Techno_ <i>DIYer</i>	
Techno_ <i>SCEPTIC</i>	
Techno_ <i>PHOBE</i>	
9.3 Conclusion	241

<u>Chapter 10: Wearable sensor collections</u>	242
10.1 Artefact collections	243
10.1.1 Wearable Skin	243
10.1.2 Customise/ Accessorise	249
10.1.3 Make(rs) & fix(ers)	254
10.1.4 Mindful Measure	259
10.1.5 Bio Sense	264
10.2 Artefact collections in context	268
10.2.1 Artefact reflection: Material, form and function	269
Material: Wearable, end-of-life considered nonwoven sensor substrates	
Form: Non-integrated form factors for in-situ wearable sensors	
Function: Early warning, detection & monitoring system	
10.2.2 Additional considerations for future development	273
Enabling technologies & supporting ecosystems	
Power generation and management	
Data contamination	
Medical certification	
User adoption	
10.3 Conclusion	277
<u>Chapter 11: Conclusion</u>	279
11.1 Designing wearable sensors for Preventative Health:	
Contributions to knowledge	281
11.1.1 Contributions to knowledge: Context	283
11.1.2 Contributions to knowledge: Practice	284
11.1.3 Contributions to knowledge: Practice methodology	286
11.1.4 Reflection & evaluation	289
11.2 Future research & work	290
11.2.1 Future work: Context	291
11.2.2 Future work: Practice	291
11.2.3 Future work: Practice methodology	293
11.3 Final comments	294

Bibliography

Publications: Books, journals, conference papers and theses	296
Internet articles and reports	305
Conference presentations and lectures	311
Primary sources	312
Additional Internet resources and references	313
Conferences and events attended	316

<u>List of figures and sources</u>	318
---	-----

Appendices

Appendix A: Wearable Technology: Issues and challenges across the lifecycle stages	335
Appendix B: QSer workshop questionnaire	348
Appendix C: User workshop questionnaire	352
Appendix D: Digital storage device	354

Definitions of key terms

Closed-loop design - A design principle, which is based on the understanding that all components used in the manufacture of a product can be reused, remanufactured or recycled into new materials and products, or composted, at the end of the product's life, thus enabling the reduction and elimination of waste and consequent burden on the environment.

Ecosystem - To enhance the user experience and make wearable sensors more valuable and effective, they can be integrated within a wider support system. This ecosystem can include other connected devices (such as the smartphone or other sensing devices), data transmission, software applications, interfaces/ data display and related services.

Electromagnetic radiation (EMR) - Energy, such as radio, TV, radar and microwaves, heat and light, released during certain electromagnetic processes, is referred to as electromagnetic radiation (EMR). Exposure to these emissions from sources such as power lines, wireless transmitters, TVs, mobile phones and microwaves is increasingly viewed as a threat to human health, although concrete scientific research to evaluate such impacts is still scarce.

Participatory Action Research (PAR) - Participatory Action Research is a people-centred, established form of experimental, qualitative research that incorporates both participatory and action components, in order to plan, design, conduct, reflect upon and evaluate a specific piece of research. PAR allows the researcher to immerse themselves into a particular community in order to develop a deep understanding for people and their practices, thus involving them in the creation of solutions to particular questions or problems.

Preventative Health - In contrast to a traditional healthcare approach, which involves disease management and treatment, preventative healthcare focuses on the prevention of ill health and disease and further benefits from people taking an active role in their own healthcare.

Quantified Self (QS) - A movement that is based on the activity of 'self-quantification', which involves engagement in gathering, managing, analysing, sharing and comparing personal data, in order to enhance personal criteria such as health, wellbeing, performance, sleep and quality of life. These activities are also described as self-tracking, self-sensing or life-logging.

QSer - A QSer is a person who participates in the activity of self-quantification through the use of analogue or digital tools and devices.

Stimuli-responsive textiles - These types of textiles fall into the broad field of 'smart textiles' and as they are capable of responding to a variety of pre-determined stimuli from the environment or the wearer, can be utilised to create wearable sensors (see below).

User-centred design - A well-proven method in academic and commercial design research, also referred to as human-centred design, which involves direct connection with potential users to identify their needs, desires and preferences, in order to gain a better understanding of the user to be able to design and develop more suitable and effective consumer products and services.

Volatile organic compounds (VOCs) - VOCs are naturally occurring gases, which are emitted by human bodies (i.e. through skin, breath and human body fluids), or man-made or naturally occurring gases in the environment, some of which can be harmful to human health (i.e. household cleaning products, paints and varnishes and cosmetics).

Wearables - The term wearables is often used in place of Wearable Technology, however, within the framework of this research 'wearables' is used to refer to any items, such as clothing, accessories (including jewellery, watches, patches, tattoos and plasters) and footwear that can be 'worn' (i.e. on the skin, on the body or inserted/ attached to an item of clothing, accessory or footwear) by the user in various locations on and near the body and include both technical and non-technical items.

Wearable sensors – In general, sensors are defined as devices that are capable of detecting and measuring particular types of inputs (physical properties and characteristics) of their environment, while consequently providing a responsive output that can be converted into readable information. Wearable sensors refer to clothing, accessories or footwear made with sensor-enabled textiles or materials; or clothing, accessories or footwear enabled by integrated or attached electronic or non-electronic sensing elements. These devices are able to sense and react in a pre-programmed manner to a wide range of stimuli, both from the wearer or the environment, in order to provide a range of actionable feedback and can be considered a sub-category of Wearable Technology.

Wearable Technology - Due to the extensive range of applications ranging from portable electronics, such as smartphones and electronic accessories, such as belts, watches and adhesive patches, to electronics integrated into or attached to clothing or textiles, there are many interpretations of this term. Used in the context of this research, Wearable Technology describes wearable items, such as clothing, accessories or footwear, which are worn to provide the user with a specific experience and are generally enabled by electronic elements and power.

Chapter 1: Introduction

This practice-based PhD project was conducted on a full-time basis over three and a half years, from 2011 to 2015. The research explores the design of wearable sensors, which refer to clothing, accessories or footwear, made with sensor-enabled textiles or materials; or clothing, accessories or footwear enabled by integrated or attached electronic or non-electronic sensing elements and can sense, react or adapt in a pre-programmed manner to a wide range of stimuli from the wearer or their environment. Wearable sensors can be considered as a sub-category of Wearable Technology, which, in the context of this research describes wearable items, such as clothing, accessories and footwear, worn to provide the user with a specific experience and are generally enabled by electronic elements and power.

The research is driven by an initial review of various issues and challenges for the design and development of textile-based Wearable Technology in general (Prah, 2012, appendix A) and the findings of an extensive contextual and literature review of wearable sensors and their construction, materials and applications, including academic research and conceptual and commercial developments (chapter 2). The issues, challenges and opportunities for the design of wearable sensors are too expansive to be addressed in one project and in line with my personal interests and professional design background as a textile, clothing and accessory designer and the evaluation of the findings outlined in chapter 3, this research focuses on a manageable set of gaps in knowledge and consequent opportunities for design innovation (chapter 3).

These four key under-explored areas, which provided relevant, personally inspiring and valuable focal points for the project, can be summarised as follows:

- **Designing for Preventative Health** - The financial burden on global healthcare system, caused by the rapidly growing numbers in chronic diseases and illnesses has reached unprecedented levels (United Nations, 2011; Halpin, Morales-Suárez-Varela and Martin-Moreno, 2010). In response to this urgent challenge, attention has been shifting from the traditional approach of disease management and treatment towards prevention, which sees the user's role changing from a passive to an active one. Preventative healthcare has thus become a key focus for innovation

and wearable devices could enable the user to engage in a 'preventative lifestyle' (Kirstein *et al.*, 2007), in order to contribute to the reduction and prevention of ill health and disease in the future. This research therefore investigates the design of wearable sensors, which could act as early warning, detection and monitoring systems, based on biochemical and environmental sensing, which was identified as an under-explored field (chapter 3);

- **Designing for the product's end-of-life** - The lack of literature, research activity and commercial development around the concept of designing Wearable Technology with solutions for the product's end-of-life in mind (chapter 3) provides strong evidence that most stakeholders either do not consider their developments a potential environmental threat at end-of-life, or do not feel it is their responsibility to provide solutions to alleviate any potential issues. As an important starting point and one aspect of contributing to knowledge on how end-of-life thinking could be integrated into the Wearable Technology design process (Köhler, 2008; 2013), this research examines the development of sensor material substrates which are designed to be disposed of responsibly or remanufactured or recycled into new products, when the user wants or needs to discard the product;
- **Designing non-integrated types of wearable sensors** - Non-integrated wearable sensors have recently emerged for sports, specialist and medical applications, producing groundbreaking innovations such as skin-worn patches, plasters and tattoos but have not yet been explored in any depth for general lifestyle use (chapters 2 and 3). A non-integrated approach in a general health and lifestyle context could provide promising alternatives to seamlessly embedded sensing into garments and accessories, where electronic and other functional elements are integrated permanently into the product, thus potentially offering opportunities to produce devices that are more affordable and easy to wear as part of an everyday lifestyle, as well as providing suitable end-of-life management strategies (chapter 3);
- **Designing for a real user need** - The Wearable Technology community is often criticised for cashing in on fleeting trends by producing short-lived gadgets, based on pushing new enabling technologies, materials and applications without first exploring real user needs and preferences (chapter

3). Inspired by the diverse choices of methods for user-centred design that already exist (chapters 8 and 9), this project proposes to explore creative approaches for the integration of a thorough user-needs investigation into the early stages of the design process, so that the findings can inform and inspire the subsequent design of the wearable sensor collections.

1.1 Research Motivation

My interest in this research project originated in a call for applicants for a Creative Industry Knowledge Transfer Network Studentship (EPSRC) at London College of Fashion, University of the Arts London, in early 2011. The research was described to focus on the investigation of novel applications for health monitoring through clothing, and to be carried out in collaboration with an industrial partner. With my background in sportswear, clothing and conceptual textile design and a strong interest in the connection of health and wellbeing with clothing and textiles, I considered this the perfect opportunity to commit to an extensive creative investigation of new applications for sensor-enabled textiles, which in 2011, were already beginning to make an impact in the sportswear industry. Although the initial research proposal evolved due to a change in industrial collaborator prior to commencement, the opportunity to explore new textile-based applications for sensor-enabled clothing and accessories remained, as the new collaborator was keen to investigate alternative applications for their portfolio of stimuli-responsive sensing technologies.

As a consumer I have experienced an aversion to many commercially available Wearable Technology products, in particular those described as infotainment & communication (chapter 2), while as a designer I felt a growing interest in how Wearable Technology will affect the realm of sports, fitness, health and wellbeing in the future. In the context of this research I consider my critical stance on Wearable Technology an advantage, as I was able to be analytical without restraint, in order to constructively highlight issues and challenges, while demonstrating future opportunities for wearable sensor design in a positive manner.

1.2 Format and role of practice

The research was further motivated by my desire to explore the role of practice in an academic context, away from the constraints of my professional practice as a trend forecaster and design consultant. My design background had a profound impact on the way I utilised practice as part of this research, as I combined familiar research methods from my professional practice, such as market research, visual research and concept boards, design sketches and sampling, with more unfamiliar techniques and procedures from the field of academic and industrial design research, including literature and contextual reviews, charts and diagrams, Participatory Action Research (an established form of experimental, qualitative research that incorporates both participatory and action components, which includes immersion into a particular community in order to develop a deep understanding for people and their practices) and artefact creation and evaluation. These tools were adapted and adopted to create a multi-method approach, which became the driver of the research methodology (section 1.4 and chapter 4) and guided the project through its various stages.

Furthermore, the creation and evaluation of artefacts played a significant role; exploratory artefacts were produced and evaluated (chapters 5-9) and informed and inspired the design of the collection of conceptual wearable sensors (chapter 10), thus embedding knowledge produced during the earlier stages of the project into the final collection of artefacts (Frayling, 1993; Scrivener, 2000). The research project was originally intended to be practice-based, as the design practice (i.e. the creation and evaluation of artefacts) was used as a method to answer my research questions and contribute to professional *practical* knowledge within the realm of textile-based wearable sensor design. However, the research outcomes go beyond practice-based contributions (chapter 11), as they further provide practice-led insights and transferable knowledge *about* practice (Candy, 2006), through the development, use and evaluation of the experimental, multi-method research methodology (section 1.4 and chapter 4).

1.3 Project aims & objectives

Although the broad aim of this research remained the same over the period of the project, more specific objectives and research questions emerged along the research journey (chapters 6,7 and 8). This process enabled me to develop a more defined focus at key stages of the research, which facilitated the interrogation of specific questions, so the findings produced at each stage could contribute to the project's complete body of new knowledge (chapter 11).

As outlined in section 1.1, the initial starting point for the project was the investigation of novel, textile-based applications for the field of health & wellbeing and based on the outcomes of my research practice in the first year of the study, this goal later evolved into the more specific objective to explore wearable biochemical and environmental sensing, specifically in the context of designing for the emerging field of Preventative Health (chapter 3). Furthermore, in line with my research motivation and background, I chose to create an industry-facing collection of artefacts, which could be utilised to inspire other researchers, designers and myself to further build on the research in the future, rather than producing user-facing and market-focused concepts and products as the output of the project.

Therefore, the main aim of this research project can be described as follows:

- To create an industry-facing collection of conceptual artefacts, which can bring attention to some of the emerging issues, challenges and opportunities around the design and manufacture of textile-based Wearable Technology in general and wearable sensors in particular, while stimulating debate and ideas for additional collaborative and cross-disciplinary research, design and development of wearable sensing devices in the future.

In order to enable the creation of these artefacts and contribute to new knowledge in this chosen field, it was necessary to define a series of achievable objectives and goals, which aimed to demonstrate the research outputs in four specific ways:

- **The identification and documentation of key challenges, gaps in knowledge and design opportunities for textile-based wearable sensors** - these identified opportunities form the starting point for this research, however, they can also be accessed and utilised by other researchers and designers to build their own work on in the future;
- **The development and application of an experimental, practice-driven research methodology** - the methodology explores diverse aspects of the design of wearable sensors including material, form and function, in order to inform and inspire the design and development of the conceptual wearable sensor collections and can further provide insights into the use of practice-based, multi-method approaches for other researchers and designers;
- **The design and development of a collection of conceptual artefacts** - these collections aim to demonstrate the complex challenges and opportunities involved in designing textile-based Wearable Technology in general and wearable sensors in particular and can be utilised as tools to inspire discussion and new ideas for cross-disciplinary future research, design and development of wearable sensors or other Wearable Technology concepts and products in the future, while providing a potential model for other design researchers to create their own artefacts;
- **To evaluate the generated conceptual artefacts and experimental research methodology** - this evaluation includes the clear documentation and communication of the outcomes and contributions to knowledge, so that other researchers and designers can build on the findings or utilise elements of the methodology in their own work.

1.4 Research Methodology summary

In order to achieve the aims and objectives, extensive consideration was given to devising an appropriate methodology (chapter 4), which could address the identified gaps in knowledge and subsequent design opportunities.

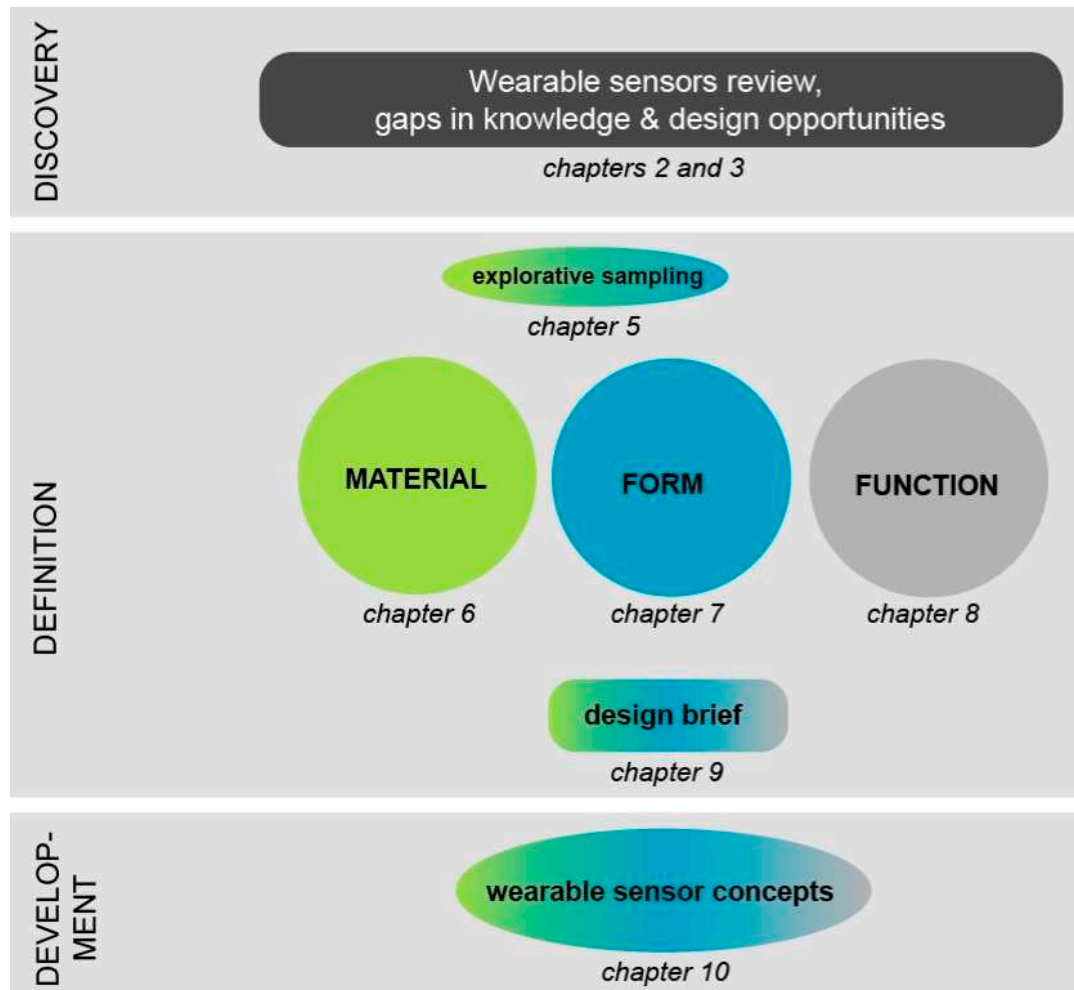


Fig 1.1: Research methodology stages, based on the first three stages of the Double Diamond model (Design Council), Prahl (2015)

In summary, the key features of this methodology can be described as follows:

- The methodology thrived on the combination of multi-methods modified and adopted both from my own professional design practice, including market research and reports, visual boards, design sketches and samples and academic and industrial design research tools including a literature and contextual review, matrices, charts and diagrams, mind maps, PAR and user workshops (chapter 4);

- The methodology was driven by these practice-based methods, which generated a wealth of qualitative data including various types of artefacts (including inspiration and concept boards, swatches and samples). These artefacts addressed the research questions and inspired further subsequent research and design in a reflective and experiential cycle of action, analysis and evaluation (chapter 4);
- The research was carried out in three distinctive phases including *discovery*, *definition* and *development*, based on the first three stages of the Design Council's Double Diamond model (chapter 4), which provided a clear framework with particular goals and objectives at each stage (figure 1.1). The discovery phase (chapters 2 and 3) comprised the literature and contextual review and identification of gaps in knowledge and design opportunities and provided the motivation behind the research. The definition phase (chapters 5-9) benefitted from an initial exploratory stage and the subsequent focus on a three-stranded investigation (material, form and function) in order to provide boundaries and research focus into particular key aspects of wearable sensor design and culminated in the application of the research outcomes to date to formulate the design brief. The development phase (chapter 10) comprised the design of the wearable sensor collections in response to the design brief and produced five collections of artefacts, which were analysed for their potential contribution to new knowledge and will be disseminated for further evaluation within the Wearable Technology community following the completion of the project.

1.5 Research questions and overall proposition

This research adopted an inductive approach and was therefore concerned with developing theory through practice-based research, in order to offer propositions based on the findings. This approach relied on the development and use of exploratory research questions, which enabled me to narrow the scope of the research, as well as making conceptual conclusions to develop an overall proposition. These research questions addressed the identified gaps in knowledge and subsequent design opportunities (chapter 3) in more detail, and emerged and developed as part of the three-stranded research practice (chapters 6, 7 and 8). The outcomes of this investigation informed the design brief (chapter 9) and inspired the

subsequent design and development of the wearable sensor collections (chapter 10).

Research questions

Material investigation:

- The 'material' investigation (chapter 6) explored the design of new types of end-of-life considered material substrates and asked the question whether a closed-loop approach (a design principle that works on the understanding that all components used in the manufacture of a product should be reused, remanufactured or recycled into new products, or composted, in order to eliminate waste and environmental burden at the end of a product's life) to material substrate design can inspire new concepts for wearable sensors

Form investigation:

- The 'form' investigation (chapter 7) focused on the design of non-integrated form factors and asked the question whether design in response to stimuli location can inspire new types, shapes and styles for in-situ wearable sensors in the context of Preventative Health

Function investigation:

- The 'function' investigation (chapter 8) examined the use case for early warning, detection & monitoring devices and systems based on biochemical and environmental sensing and while this investigation did not have one specific research question to focus on, explored different aspects and enquiries in regard to the functionality of a wearable early warning system, all of which involved the user in their exploration

As a potential solution to the reduction of the burden on global healthcare systems, wearable early warning, detection, and monitoring devices and systems, based on the capability to sense biochemical and environmental stimuli, could contribute significantly to the improvement of the user's health and wellbeing. Biochemical stimuli include internal volatile organic compounds (VOCs), which are naturally occurring gases emitted from human bodies. Environmental stimuli include external VOCs, which are naturally occurring or man-made gases and can be present in products such as cleaning products and paint, as well as potentially health-threatening levels of electromagnetic radiation (EMR), energy released from

electronic devices such as radios, TVs, microwaves and mobile phones, present in the wearer's ambient environment.

In order for these types of devices to be efficient as part of a preventative approach to healthcare, they need to be available to and adopted by a significant number of users. The overall proposition of this research therefore asserts that:

- *Wearable sensors should be designed to integrate easily into the user's existing lifestyle, routines and outfits, in order to engage a broad section of the global population in a preventative lifestyle*

Combining the outcomes of the material, form and function investigations, the conceptual artefact collections aim to demonstrate *how* wearable sensors could be designed to easily integrate into users' existing lifestyles, routines and outfits, while responding to widely differing user preferences and needs and addressing the urgency for end-of-life considered and cost-effective material innovation.

1.6 Scope and limitations

An extensive review of contributions to knowledge, limitations of the research project and proposals for future research is offered in chapter 11, however this section briefly describes the scope and limitations of the project in order to clearly communicate the general framework for the research.

Particularly during the first 12 months of the project, one of the more challenging aspects of this research was the definition of the scope of the research territory and specific enquiry, as I encountered various hurdles and contextual developments:

- **A vast research territory:** Familiarising myself with the continually and fast evolving domain of textile-based Wearable Technology with the specific focus on wearable sensors;
- **Technology changes:** The rapidly growing ubiquity of smartphones impacted strongly on the progressive direction of Wearable Technology applications during the research period, as the smartphone changed from

being considered a potential threat to the innovation and adoption of new products (Lukowicz, 2012), to an enabler (Lukowicz, 2012; Burr, 2012) and useful interface for Wearable Technology (chapter 2);

- **Emergence of the Internet of Things (IoT):** The mainstream adoption of the concept of IoT, which refers to networks of interconnected objects, humans and buildings through the use of embedded electronics, software and sensors, contributed to a significant surge of research activity in sensor-enabled textiles, clothing, accessories and other wearable or mobile devices during the research period, while further exposing potential risks on data security and privacy.

Although the scoping process took much longer than anticipated, the extensive contextual & literature review (chapter 2) and overview of issues with Wearable Technology design (appendix A) were necessary tools to enable a clear perspective of the key challenges, which in line with my research interests were converted into promising design opportunities (chapter 3). By utilising this method of analysis, and clearly establishing which aspects of practice to focus on (material, form and function), I was able to create a distinct starting point from which the research was able to continue to narrow and focus its scope. While academic and industrial research in the specialised domain of wearable sensors is rapidly expanding, this research aims to produce authentic practical insights into the design of wearable sensors through the combination and investigation of three different but interconnected key areas; the design for a real user need in the context of Preventative Health (function), the design of non-integrated types of wearable sensors (form) and the design of end-of-life considered sensor substrates (material). In addition to these practice-based outcomes, the project further offers scope to contribute practice-led outcomes, based on the use of multiple and experiential methods, which can be shared with other designers and researchers in the future in a variety of ways (chapter 11).

This project was initially motivated by the opportunity to carry out academic research in collaboration with an industrial partner, thus bringing together methods from professional and academic design research and practice, in order to produce outcomes that have relevance both in academic and industrial contexts. However, although the research began, and continued for the first two years as an industrial

collaboration project, the scope and nature of the research was impacted by the unforeseen termination of the collaborative relationship in the third year, when the project was still in its definition phase. As a result, the opportunity to work with a commercially existing sensing technology to produce, test and evaluate proof-of-concept prototypes to complete the conceptual artefact collections was lost. The project therefore followed a more speculative path and expanded the exploration of the user-need perspective, while the design practice was informed by generic, rather than specific enabling technologies. As a positive consequence, the wearable sensor concepts are not dependent on any particular sensing technologies in this fast-moving field and could therefore be applicable in a broader context. However, the collections are firmly based on the understanding that, as the contextual and literature review demonstrated through the presentation of a wealth of existing and emerging technologies and applications (chapter 2), it is highly likely that a range of suitable enabling technologies will be available in the near future.

Although this change could be considered a limitation of the research, in practice it meant that I was able to concentrate on other important elements, which included the in-depth focus on wearable material substrate and form factor design and a design-driven exploration of functional and user need aspects. Furthermore the research project increased its emphasis on research methodology and context, rather than producing concrete and potentially market-focused outcomes.

1.7 Thesis overview

Introduction

Chapter 1 introduces the research by providing a brief overview of the research context, background and identified gaps in knowledge, before describing the motivation for the research, which is driven by the pivotal role of design practice. The chapter also outlines the broad and overall aim of the research, while providing an overview of the key objectives to support and enable this aim. Furthermore the chapter gives a short summary of the research methodology, research questions and overall proposition, before discussing the scope and limitations of the research and presenting a summary of the thesis structure.

Contextual & literature review

Chapter 2 provides an extensive overview of the literature, academic research and conceptual and commercial developments relevant to the research; this includes a review of the construction of electronic sensors and textiles, sensing applications for the field of Wearable Technology and emerging printable material substrates, as well as non-electronic sensors from the fashion, sportswear and diagnostics sectors.

Developing the project scope: Discovery stage

Based on the insights of the contextual & literature review (chapter 2) and the document 'Wearable Technology: Issues and challenges across the lifecycle stages' (Prahl, 2012, appendix A), *chapter 3* identifies gaps in knowledge and demonstrates resultant design opportunities for the design of wearable sensors, which are the main drivers behind the project.

Research Methodology

Chapter 4 presents the practice-driven framework that underpins the research methodology and relies on the combination of experiential and practice-based methods adapted and adopted from professional design practice and academic and industrial design research to generate diverse qualitative data at various stages of the research journey. It further describes the data evaluation techniques utilised, before outlining the process and stages of the ongoing design practice, which uses a specifically devised three-stranded investigation model, employing key methods such as Participatory Action Research and artefact creation and evaluation. Furthermore, this chapter provides reflection and evaluation of the various methods used, as well as the overall research methodology.

Design practice: Definition stage

Chapter 5 describes and documents the first steps taken into exploratory design practice, which provided some early research findings, as well as contributing to the definition of the conceptual framework for the subsequent stages of design practice. Following on from the exploratory stage, *chapters 6, 7 and 8* describe the individual research journeys as part of the three-stranded enquiry, which focus on the investigation of 'Material', 'Form' and 'Function'. *Chapter 9* conveys the process of consolidation and evaluation from the outcomes of the three-stranded investigation, which blend together to inform the design brief, which is further based on the profiling of five speculative user types and serves as the catalyst for the design of the final artefact collection.

Design practice: Development stage

Chapter 10 first presents the final artefacts (wearable sensor collections), before reflecting on the design process and resultant research findings in the context of existing and emerging developments, with the aim of contributing to new knowledge on the design of wearable sensors for Preventative Health.

Conclusion

Chapter 11 presents the conclusions of the research project as a whole, which include outcomes regarding context, practice and practice methodology. These findings are evaluated in order to communicate how they can contribute to knowledge and propose how other researchers and designers could build upon them. This chapter also suggests opportunities for further work and considers how the limitations of the research may be overcome in the future.

Bibliography and appendices

The thesis is supported by an extensive *bibliography*, which lists the various sources, resources and references (publications, Internet reports and articles, conference presentations and lectures, additional primary sources and Internet resources, conferences and events attended and image sources) utilised to contribute to the research. Further reference documents (Wearable Technology: Issues and challenges across the lifecycle stages report and two questionnaires utilised for the workshops) and a digital storage device containing additional visual documentation of the user concepts (chapter 9) and wearable sensor collections (chapter 10) are available as appendices.

Chapter 2: Investigating wearable sensors

The broad starting point for this research was to explore and develop stimuli-responsive textiles, which could provide sensory functionality to the user in response to pre-determined stimuli, and therefore be utilised to design and create wearable sensors. In general, sensory functionality can be described as the ability to transmit information in response to stimuli, while sensory textiles in particular are widely accepted to describe electronically conductive fabrics, which can act as switches and sensors (Swallow and Thompson, 2001) and subject to the particular enabling technology utilised, these textiles can respond to a variety of stimuli.

Stimuli-responsive textiles fall into the broad field of 'smart textiles'. Although a multitude of terms and understandings exist in this field, one of the most widely quoted definitions of smart textiles is that by academic researcher, educator and author Xiao-Ming Tao, who is known for her research work on smart materials, including nanotechnology and photonic and electronic fibres and fabrics. This definition states that smart materials and structures can sense and react to environmental condition or stimuli, which can be from mechanical, thermal, chemical, electrical, magnetic or other sources (Tao, 2001, p. 3). The field of smart textiles is vast and continuously evolving and is the result of collaborative research between the domains of nanotechnology, microelectronics, information technology and textile technology (Ossevoort, 2013), which comprises a multitude of technologies such as photo and thermal sensitive materials, fibre-optics, conductive polymers, shape memory materials, intelligent coatings and membranes, chemical responsive polymers, mechanical responsive materials, micro-encapsulation and micro and nano materials (Tao, 2001, p. 4).

However, this research project focuses only on smart textiles and materials that could be utilised to create wearable sensors, which are able to sense and react in a pre-programmed manner to a range of pre-determined stimuli from the wearer or the environment. In general, sensors are defined as devices that are capable of detecting and measuring particular types of inputs (physical properties and characteristics) of their surrounding environment, while consequently providing a responsive output that can be converted into readable information. In the context of this research, wearable sensors denote clothing, accessories or footwear that can be worn on or near the body, in order to sense and react to stimuli from the wearer

or the wearer's environment to provide a range of actionable feedback. Furthermore, this project differentiates between *electronic* wearable sensors and *non-electronic* wearable sensors. Electronically-enabled wearable sensors can be described as a sub-category of Wearable Technology, encompassing clothing, accessories or footwear made from electronic, sensor-enabled textiles and materials, or clothing, accessories or footwear made with integrated or attached sensing elements, while non-electronic wearable sensors include clothing and accessories which can provide simple visual feedback, such as colour and pattern change in order to visualise a response to selected stimuli (section 2.2).

Although these two types of sensors are enabled through different technologies, they have several attributes in common; a) they utilise material substrates that have been equipped with stimuli-specific sensory functionality during the manufacturing process (i.e. construction or surface treatment), b) they are wearable on or near the body or portable/ hand-held with potential to be made wearable in the future and c) they provide a warning, detection or monitoring mechanism to inform the user/ wearer about their health status or the state of the environment they are in. Nonetheless, they are distinguished through their level of activity and response, which concerns the complexity of feedback and user interaction. While electronically-enabled sensing devices (section 2.1.) can offer the user a wide range of options on visual, tactile (i.e. vibrate) or other feedback, data collection and management and user control and interaction (often through integration into a wider ecosystem, which can include other connected devices, data transmission, software applications, interfaces/ data display and related services), non-electronic sensing devices can only provide the user with basic visual feedback and the feedback remains more or less the same (section 2.2). User interaction for these types of sensors is far more limited, as there are no interfaces for the user to engage with. However, some of these simpler types of wearable sensors can physically collect samples from the wearer or environment, which brings alternative opportunities to in-situ/ on-body data analysis, as collected samples can be analysed and evaluated away from the wearer's body.

By investigating beyond the scope of electronically-enabled wearable sensors, this research aims to highlight opportunities for the design of wearable sensors, which could address a broader range of user needs and preferences in terms of cost, availability, wearability (achieved through considered design of materials and form factor) and functionality. Furthermore, although this project is concerned with the

design of wearable sensors utilising textiles and wearable materials (chapter 6), this review also looks at some examples of hardware, such as wristbands and jewellery, as the growing interest and use of these types of items provides insights into user needs and preferences in regard to wearing sensors.

2.1 Electronic wearable sensors

Degrees of sensor integration

With a view to electronic wearable sensors, it is important to investigate the various degrees of integration. There are many ways to characterise degrees of integration and studying Kirstein *et al.* (2007), Catrysse, Pirotte and Puers (2007), Seymour (2008) and Moehring (2012) has been particularly helpful in defining my own classification for this project. Building and expanding on a systematic review of literature and academic and industrial examples of various types of electronic wearable sensors, this research identifies three types of electronic wearable sensors (fig. 2.1), in order to provide a more diverse scope for innovation. These sensors are defined by how sensory functionality is delivered to the wearer and comprise:

- **Textiles** as the sensor carrier
- **Clothing** as the sensor carrier
- The **body or skin** as the sensor carrier

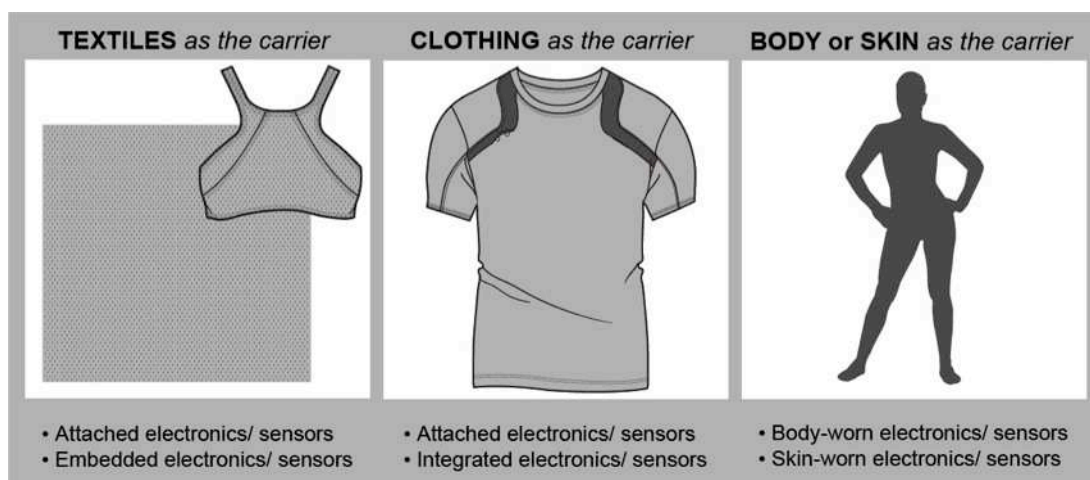


Fig 2.1: Three types of electronic wearable sensors, Prahl (2015)

Textiles as the sensor carrier:

This approach utilises the textile as the carrier for sensory functionality and this can be achieved in two ways: a) electronics and/ or sensing elements are attached permanently to the surface of the textile or b) the textile itself *becomes* the sensor, as electronic sensing functionality has been embedded directly into the material during textile manufacture (section 2.1.1). Academic and professional researchers Catrysse, Pirotte and Puers (2007), refer to these two types as '*embedded electronics*', textiles with built-in existing electronic components, and '*textronics*' and '*fibertronics*', where electronic components are either manufactured by textile production techniques, or where electronics are integrated directly into the yarns. Yarn-embedded electronics have recently attracted much interest, as researchers from Nottingham Trent University's Advanced Textiles Research Group led by Tilak Dias, have received around £1.2 million in funding to develop fibre electronics, including sensors, LEDs and micro-controllers (Nottingham Trent University, 2015).

Much of the ongoing research and development into wearable sensors has been focusing on this type of seamless integration to create textile sensors and academic researchers and educators at Georgia Institute of Technology in Atlanta, Park and Jayaraman (2001) described this approach as the 'skilful blending' of computing elements with the textile, further considering the smooth integration of the diverse elements required, such as the interconnect architecture, hardware and system software, within the fabric infrastructure. As part of my classification, in both cases the textile is equipped with sensory functionality during the yarn or textile manufacturing process, *before* it is made into a garment or accessory and the integration of electronic elements is permanent, although in theory, where electronics have been attached to the surface of the textile, they could be taken off, if they have been designed and manufactured with disassembly in mind.

Clothing as the sensor carrier:

This approach utilises clothing as the carrier for sensory functionality and this can be achieved in two ways: a) electronics and/ or sensing elements can be attached to or integrated into specific items of clothing *during or after* garment manufacture or b) electronics and/ or sensing elements can be attached to various items of clothing *after* garment manufacture by the user. US based Wearable Technology designer, researcher and academic Seymour (2008) differentiates between the technology being physically embedded or attached into clothing or clothing simply being a container for the technology and the key difference in my classification is that one

approach is *garment-specific* and *semi-permanent* and therefore not easily reusable with any other items of clothing, unless great effort is made to extract the sensing elements from the original garment, while the other approach provides easy options to remove and reuse existing sensing elements with a range of other items (section 2.1.2).

Body or skin as the sensor carrier:

Body-worn wearable sensors include accessories that are specifically designed for the purpose of sensing (i.e. they have no other function such as keeping any particular body-parts warm or clothed) or accessories that are being worn for functional or aesthetic reasons (such as ear buds or jewellery) and have an additional capacity to provide sensory functionality. Wearable computing researcher and colleagues, Kirstein *et al.* (2007) considered electronic accessories, such as watches and belts, one of the first steps to wearability and although this research does not aim to design any hardware, the emergence and success of items such as watches, wristbands and various types of other activity trackers, are relevant to the investigation, as they provide important insights into changing user needs and preferences. *Skin-worn* wearable sensors include adhesive patches, plasters and tattoos and have recently emerged in the healthcare & medical arena, where in-situ sensing for disease detection, monitoring and management plays an important role, although researchers and developers are also beginning to explore applications for these types of sensors in the sports & fitness arena.

Textile-attached and embedded, clothing-integrated and attached, and body and skin-worn sensors have been utilised across a variety of commercial products, research projects and conceptual developments and the functional requirements of a product are likely to dictate the more suitable type of sensor; i.e. in wearable health systems and most sensor-enabled textiles for physiological sensing or monitoring, it is generally essential to provide large-area skin contact for accurate measuring, in which case softness and comfort are a key requirement likely to benefit from the use of textile embedded sensors, while sensors functioning as switches in order to operate a device (i.e. integrated remote control buttons) generally only need a small contact area to function and thus make the use of attached sensors viable.

2.1.1 Wearable sensors: Textiles as the sensor carrier

Electronic stimuli-responsive textiles can be considered a particular type of smart textile, which is referred to as electronic or e-textile. These conductive textiles can change their electrical properties as a result of responding to a wide range of internal and external stimuli and can therefore be used as sensing textiles or sensors. The advantages of utilising textiles as sensors are that, depending on their method of integration, they can be flexible, soft, comfortable, wearable, washable and easy to use. Generally, textiles have a low electric conductivity but conductive components can be added and integrated during the manufacturing process. Therefore conductive textiles can be created in two ways, either by utilising specific construction methods to integrate conductive and electronic elements during the textile manufacturing process, such as knitting, weaving and felting or other nonwoven processes, or through surface treatment of the finished textile substrate, which includes printing, coating, lamination, embroidery and appliqué.

Integration and construction methods utilise conductive yarns and threads and fibres, which can be separated into two categories; intrinsically conductive fibres including pure metals such as stainless steel, titanium, aluminium, nickel, copper and carbon and conductive polymer fibres, or specially treated fibres, which are generally a composite of metals and non-conductive materials and can be produced by blending or coating fibres with metals and metal substances to achieve conductivity. Within the textile infrastructure, conductive fibres, yarns and threads allow electricity to flow to and from the various components, thus enabling and creating what is often referred to as a smart textile network. Senior researcher at Fraunhofer Institute Germany, Torsten Linz (2007), commented on the lack of quality and suitability of conductive threads for the purpose of energy and data transmission, as these were originally developed for anti-static and anti-bacterial purposes, and their conductance, processability, signal transmission capability and reliability need to be improved to ensure textile and material innovation in this field. However, some of the examples presented, highlight promising development opportunities around textile-based wearable sensors, which are created through construction and surface treatment.

Construction

Knitted fabrics are well suited to next-to-skin applications in clothing, which are utilised to achieve the desired sensory functionality and comfort of the textile and

garment. Knitting techniques can include plain knitting, circular knitting, warp knitting or crocheting with conductive yarns (Catrysse, Pirotte and Puers, 2007). Based on a series of experiments with knitting technology concepts, Hong Kong based academic researchers Li *et al.* (2009), stated that the traditional technology of knitting has exciting potential for new sensor-enabled clothing, as it is able to utilise various types of knitting to enhance function.

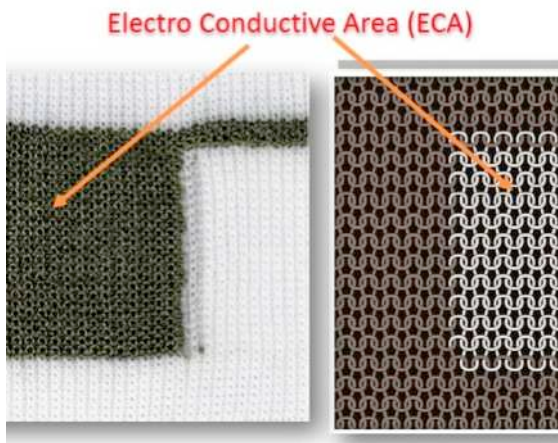


Fig. 2.2: Knitted electrically active structure, NTU



Fig. 2.3: Aeolia Cello stretch sensor

Academic research examples include work at Nottingham Trent University, which presents the exploration of electrically active knitted structures (fig. 2.2) through the use of computerised flat-bed knitting technologies to create seamless knitting and the encapsulation of electronic activity into fibres and yarns directly (Dias, 2013). Further evidence of the innovative use of knitted materials for textile-based functionality was demonstrated with the academic/ artist collaboration 'Aeolia', which was funded by New Media Scotland and explored the use of commercially available stretch sensors through the creation of a collection of garments (Kettley, 2013). The image (fig. 2.3) shows Aeolia Cello, which was made from knitted stretch sensors in combination with conductive yarn to create a wearable musical instrument.



Fig. 2.4: Numetrex knitted sensor close-up



Fig. 2.5: Pressure sensitive 'Smart Sock' prototype

The Numetrex sports bra ^{2.1T}, utilises textile electrodes that are knitted directly into the front of the bra (fig. 2.4) to maintain contact with the wearer's skin to sense the heart's electrical pulse during exercise, while a similar example, the 'Smart Sock' (fig. 2.5), developed by functional textile company Alphafit in Germany in 2011, is a pressure sensory sock made of sensory filaments, which can measure surface pressure on three-dimensional variable surfaces, without the need to insert any industrial sensors, as the filament itself measures the pressure.

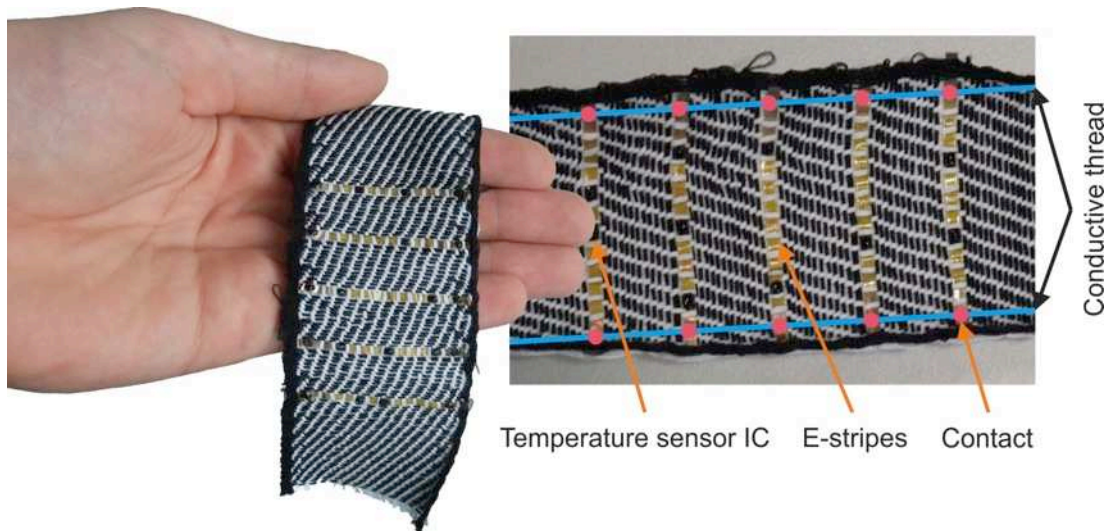


Fig. 2.6: Woven temperature sensor ETH Zurich

Electrically conductive woven textiles can be manufactured through construction or coating; for construction methods, conductive threads are woven in combination with non-conductive threads to provide an electrical circuit while staying soft and flexible. The limitations of using weaving methods to produce electrically conductive textiles were highlighted by Ghosh, Dhawan and Muth (2006), academic

researchers from NC State University, Raleigh, who pointed out that conductive threads have to be placed in specific locations in the warp direction to function, thus potentially restricting aesthetic and creative possibilities. Therefore it is necessary for designers to consider the restrictions of integrating traditional electronic components by weaving with regard to comfort and restriction of movement.

In 2010, scientists from the Wearable Computing Lab at ETH Zurich developed intelligent textiles that have electronic components such as temperature sensors and conductive filaments woven into them by integrating microchips and other microelectronic elements directly into the textile architecture (fig. 2.6). This technology enables mass-production on conventional machinery and provides washability at 30 degrees, due to the electronic fibres being encapsulated (ETH, 2010). Another woven example is the 'Stress vest' ^{2.1A}, which was developed as part of the ConText project and has sensors directly woven into the fabric. The sensors can register the electrical excitation of the muscles and thin conducting metallic fibres pass the signals to an electronic analysis system, in order to sense and determine the level of physical stress.



Fig. 2. 7: Needle felted touch sensor



Fig. 2.8: Needle felted motion sensor

Most commercially available conductive nonwoven materials are produced through coatings and plating, however, on a more experimental level, several research and design projects explore the creation of nonwoven conductive textiles through integrating conductive yarns and fibres through the process of felting. A touch sensor (fig. 2.7), presented by online resource www.adafruit.com, was created through the process of needle felting, which integrated conductive felt touch buttons suitable for use with a capacitive touch sensing circuit, while the FELT-ME glove and hand warmer (fig. 2.8) is made with merino wool and steel fibres to form

pressure sensor pads that control embroidered LEDs to light up in different intervals and speeds, resulting in an interactive glove that responds to the wearer's grip (Lim, no date). Electronic textile designer Lynne Bruning, who needle-elts wool roving and conductive thread to craft her own electronic textile sensors, switches and wearable computing fabrics to provide a greater variety of aesthetic and tactile choices, highlighted that conductivity depends on how densely the material is felted and it is important to work with a multimeter while felting, in order to test resistance and electrical standards, while making sure the fabric meets aesthetic requirements (Bruning, no date).

Surface treatment

Further to sensor integration through construction methods, sensing and electronic elements can be added to the finished textile through printing, plating, spraying, lamination or impregnating during the finishing process. Conductive paints and inks, including carbon, copper and silver can be used to paint or print circuits and various types of sensors onto a variety of fabrics, although care needs to be taken on stretchable fabric in order to avoid cracking of the print to ensure conductivity. The current interest and increasing activity in the development of printing techniques for electronically conductive and sensing textiles appears to be driven by two key factors; printing techniques potentially offer cheaper and simpler manufacture than conventional techniques, while the need to design flexible, bendable textile electronics systems able to conform around bodies without interfering with comfort or movement, is also pushing innovation in this field. Conductive inks and pastes include silver, carbon, copper or polymer and are suitable for a variety of printing or other application techniques. Screen-printing is often used to apply inks and pastes to fabric substrates, as other techniques such as painting and spraying are also being explored to find the most suitable application methods for the various fabric substrates available.



Fig. 2.9: Printed chemical sensors

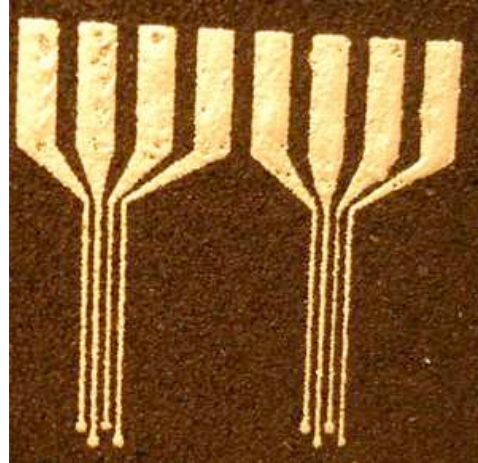


Fig. 2.10: Electrode sensors printed on neoprene

Chemical sensors are predicted to have a significant impact on personal health and wellbeing in the future, and printing offers promising opportunities in this field.

During work funded by the U.S. Office of Naval Research, engineers at the University of California, San Diego Jacobs School of Engineering, established that due to the tight contact and exposure to the skin, chemical sensors printed directly on elastic underwear waistbands (fig. 2.9), can accurately detect changes in the wearer's body chemistry, while retaining their sensing abilities even after engineers stretched, folded and pulled the chemical-sensing printable electrodes ^{2.1B}. Another research project at the same university investigated the printing of electrochemical sensors directly on neoprene wetsuit material (fig. 2.10) and proved that this approach produced extremely flexible circuits that can be pulled and pushed and are suitable for in-situ use in seawater (Jacobs School of Engineering, 2011).

The National Physical Laboratory in the UK developed a technique, which could allow lightweight conductivity to be printed directly onto complete garments. This technique involves chemically bonding a conductive silver layer, which fully encapsulates fibres and has good adhesion and excellent conductivity and can be easily printed onto many different types of fabrics (National Physical Laboratory, 2013). In a similar vein, Swedish academic researchers at the University of Borås, Rehnby, Gustafsson and Skrifvars (2008), discussed the use of conductive polymer coatings, which can be applied directly to the surface of the textile, to provide the necessary qualities for smart wearable textile applications.



Fig 2.11: Stitched stroke sensor

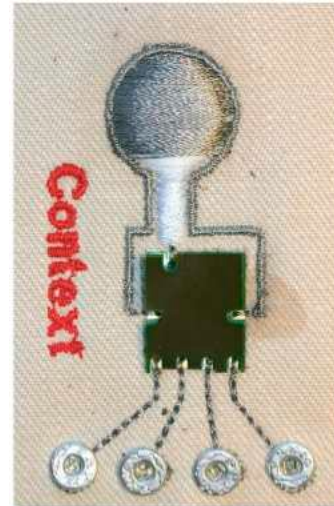


Fig. 2.12: Embroidered sensor

In addition to printed and coated technologies, sensors can also utilise conductive embroidery by itself or in combination with other conductive textile materials. The stroke sensor (fig. 2.11) by Hannah Perner-Wilson from design collective www.kobakant.at, is made with silver-plated nylon conductive threads stitched into a neoprene substrate, working with a technique similar to hooked rug stitching. When stroked, the threads make contact with a piece of conductive fabric attached on the reverse in order to function like a contact switch. Academic researchers from KU Leuven in Belgium, Taelman *et al.* (2007) describe an embroidered stress sensor (fig. 2.12), which utilised a multi-layer embroidery process to build a contactless EMG sensor with the same thread that is used for interconnection with the electronic network.

Electronic sensing networks

Electronic wearable sensors sense and gather data from the wearer or the environment and are capable of relaying the information to a processing unit through an electronic network. In order to enable a textile-embedded/ attached wearable electronic system or network, it is necessary to create electrical circuits, which integrate and interconnect the various electrical components (i.e. sensors, actuators and power supply), so that the sensing element is able to electronically communicate the gathered data to a processing unit. This means that, subject to the addressed user need and technology used, the textile can react to provide the wearer with immediate response (i.e. visual signal) and/ or the data can be communicated to the processing unit for analysis by a selection of connected devices, such as computers, tablets and smartphones.

These enabling circuits and interconnections can be manufactured by way of embroidery, printing and lamination. Employing embroidery to create conductive tracks and interconnections has functional advantages, as it is soft, flexible, tactile, durable and washable and can be used on most textile substrates. Academic researchers at MIT Media Laboratory, Post *et al.* (2000), described electronic embroidery or e-broidery as the embroidery of a conductive structure to a ground structure, whereby the embroidered circuits and patterns can be applied through manually or machine controlled sewing and stitching techniques. Ghosh, Dhawan and Muth (2006) further identified that one of the advantages of embroidery is the relative freedom in regards to the direction and shape of the threads. However, yarns and threads for e-broidery must be chosen carefully for their suitability, as they need to be flexible and strong to avoid breakages during sewing, wear and maintenance, and conductive enough to function and perform within a textile circuit.



Fig. 2.13: Embroidered connections for sensor feedback



Fig. 2.14: Embroidered connections

One example of embroidered circuits and networks is the conceptual Climate Dress designed by Danish design company Diffus, which was presented at the Bright Green Expo in Copenhagen in 2009 to highlight environmental issues through an aesthetic display of environmental data. The dress utilised hundreds of CO₂ responsive LEDs, which were enabled by a Lilypad Arduino microprocessor and a carbon dioxide detector and connected into a wearable sensing system with decorative conductive embroidery (fig. 2.13), which was developed by Forster Rohner AG ^{2.10}, a Swiss family run embroidery specialist with over 100 years of embroidery experience in the fashion industry. Conductive embroidery was also employed in a research project carried out at Fraunhofer Institute Germany, which explored the design of a t-shirt (fig. 2.14) capable of measuring EKG signals from

the wearer. The researchers described the EKG shirt as the first application to investigate an interconnection technology based on embroidery of conductive yarn (Linz, Gourmelon and Langereis, 2006), and the system comprised an EKG module on a flexible substrate, snap fasteners for a removable battery and embroidered electrodes and conductors. Other academic research into the use of electronic embroidery includes Georgia Tech's Textile Interface Swatchbook, and this project is aimed at fashion designers in order to demonstrate the versatility of electronic textiles and to inspire their use for a broader audience (Zeagler, 2012).

With regard to printed circuits and interconnections, silver, carbon, copper or polymer based conductive inks and pastes can be suitable for a variety of printing or other application techniques including screen-printing and other techniques such as painting and spraying. Although printed electronics and circuits are mostly chosen for the production of paper-based and highly flexible and soft film or foil-based substrates as seen in the packaging industry, there are some examples of printed circuits and interconnections on more conventional textile substrates. However, to date printing circuits and interconnections on fabrics remains problematic due to textile surfaces, stretching, washing and wear and tear and following rigorous testing, researchers at the National Textile Center, USA, have raised concerns about printed inks degrading through cracking and peeling and losing conductivity after twenty-five wash cycles (Pourdeyhimi *et al.*, 2006). In response, the research developed a mechanism to control durability of the printed circuits through a breathable, thermoplastic melt-blown coating, which protects the printed circuits from wash damage and fracturing. A more recent research project at Ghent University also illustrated that by applying a protective thermoplastic polyurethane layer on top of the conductive screen print, washability was improved while conductivity remained intact (Kazani *et al.*, 2012).

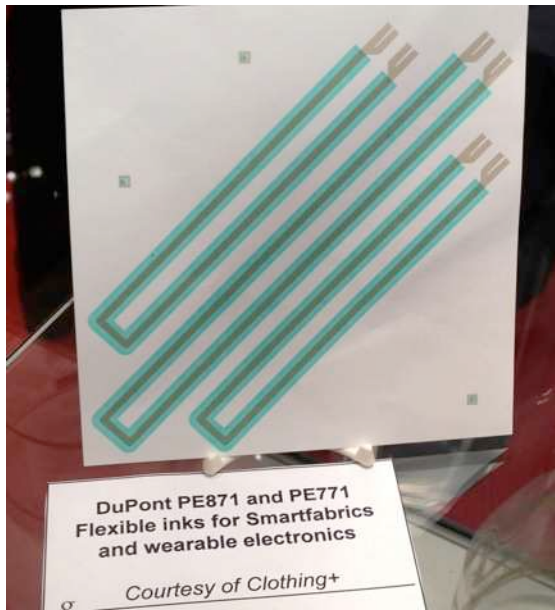


Fig. 2.15: DuPont flexible inks



Fig. 2.16: Conductive paste on nonwoven

In order to explore future opportunities for screen-printing in a textile context, it will be beneficial to shift the focus to more appropriate and unconventional substrates, and DuPont showcased their new generation of functional, flexible and stretchable electronic ink materials for smart clothing and other wearable electronics at the Printed Electronics Show 2014 in Berlin (fig. 2.15). In 2006, the European Commission co-funded STELLA project ^{2.1D} already developed a new technology platform for stretchable and breathable circuit boards, which utilised printed conductive paste on nonwoven material substrates (fig. 2.16) to explore new approaches for wearable electronic systems.

In addition, the development of conductive inkjet printing for textiles also shows great potential. Many specialist manufacturers are already using this technology for producing transistors, printed circuits and solar cells, as well as RFID tags and temperature sensing directly onto packaging, although examples of textile applications are still hard to find. Materials scientist at the University of Illinois have developed silver ink that is suitable for inkjet printing and other application methods due to its low viscosity printing and it is believed to be suitable for a wide range of flexible materials including fabrics (Zyga, 2013), while researchers at the University of Leeds have been experimenting with a novel method of printing metallic electrical conductive patterns on different substrates by ink-jet printing of metal salt solutions, concluding that with further development and depending on the substrate, this method could be used for printing electronic devices onto a large range of materials in the future (Bidoki *et al.*, 2004).

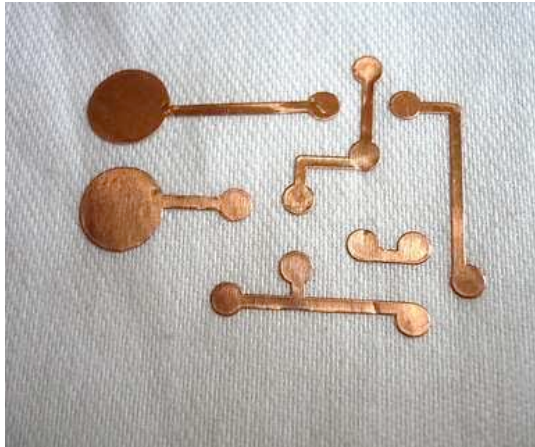


Fig. 2.17: Flexible copper foil circuit



Fig. 2.18: Laser cut adhesive traces

More unconventional ways to create circuits and traces include the lamination of a variety of conductive materials onto the textile surface. Particularly useful are adhesive materials such as conductive tapes, including nickel, copper and cobalt coated nylon rip-stop anti-fray tape, which can be laser cut into customised designs and shapes. Kobakant explore the making of flexible, textile-based circuits and these include the use of a vinyl cutter to cut copper foil into a circuit shape, before depositing the foil onto the substrate and soldering electronic components to the foiled design (fig. 2.17). In a similar lamination process, MIT researcher Nadya Peek's experimented with conductive traces for use on stretchy fabric (fig. 2.18), after ironing on adhesive sheeting to the conductive fabric, the double-layer material is laser cut into the required designs and then ironed on to the desired substrate or garment (Peek, no date).

2.1.2 Wearable sensors: Clothing as the sensor carrier

This section looks at examples of wearable sensors, which are produced through integration in or attachment to specific items of clothing, making them garment-specific; or attachment to various items of clothing in a removable and reusable manner. Garment-specific integration can include the attachment of the sensing element to the outside of the clothing, or it can be hidden inside, such as pockets or stitched or sandwiched into seams or linings. This means that the wearable sensing element can only be worn with the original item it was integrated with or attached to, as disassembly is possible but not planned for. On the other hand, there are some rare examples of removable sensing elements, which could be inserted or attached to any clothing, accessories or footwear of choice by the user.

Garment-specific integration

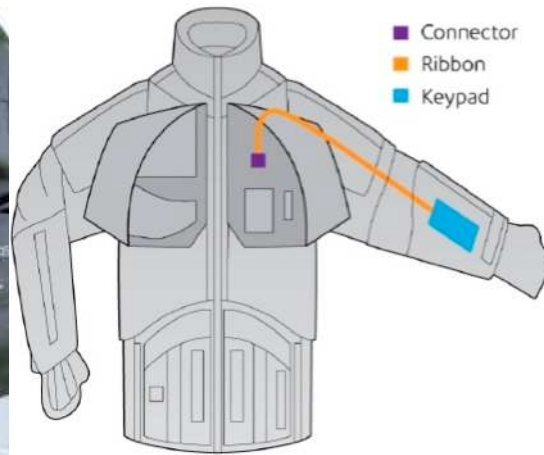


Fig. 2.19: BURTON jacket with remote control Fig. 2.20: Internal control pad and textile cable

Clothing with integrated ‘infotainment’ such as Burton’s iPod jacket buttons (fig. 2.19) and a Marks & Spencer business suit described in section 2.1.5 (fig. 2.47), launched in 2003 and 2007 respectively, utilise flexible control pads, which are touch-sensitive, in order to operate the wearer’s connected devices such as music players and mobile phones. External printed buttons provide the interface for a control pad, which connects to the device kept in the chest pocket via a textile cable (fig. 2.20) to transfer the data. As the keypad and cable are sandwiched between the jacket’s outer material and lining, it would not be practical to disassemble the sensing element to use with other garments and would further need a connector to attach to the wearer’s device of choice.



Fig. 2.21: Sense t-shirt and sensor details

The Sense t-shirt (fig. 2.21), created as a joint venture between Swiss non-profit research company CSEM and Sports Unit of Innovation in 2008, is a portable system capable of continuously monitoring physiological signals such as

electrocardiogram, respiration, blood-oxygen saturation, or body temperature. Electronic sensors can be 'clicked' into specific locations within the t-shirt (fig. 2.21, right) and are connected through conductive embroidery paths (CSEM, 2010). In a similar manner, the Under Armour's E39 compression shirt (fig. 2.22), which was first launched to professional National Football League players in 2011, is fitted with a removable 'bug' sensor. However, although the sensor is described as removable, this is likely to be a feature to make washing of the shirt easier, rather than being able to use the sensor with other garments, as it relies on the garment's infrastructure and integration point to function.

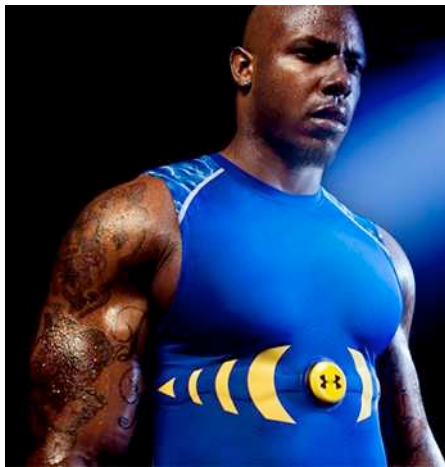


Fig. 2.22: Under Armour sensing shirt



Fig. 2.23: First Warning System sensor bra

The First Warning System, renamed to Cyrcadia Health in 2014 (fig. 2.23), cancer-detecting bra, integrates a complex sensing system, which has been 20 years in the making and was originally designed as a fixed sensing platform, as seen in the prototype above. More recently the company have focused on versions that are removable by developing a small device that can be inserted into the user's existing bras, for monthly breast wellness screening in the privacy of their own home and they are also in talks with collaborators to develop versions that can be embedded into regular sports bras (Salber, 2014).

Removable/ flexible attachment

There are a small number of examples for attachable wearable sensors, which can be used with various items of clothing or footwear, although levels of attachment vary from sensors that are a) designed to fit into pockets or cavities in specific shoe models, to sensors that b) can work with many different types of footwear, such as sensor integrated insoles, to c) sensor accessories, which are merely attached to any garment or footwear the user wishes to wear. Both Nike and Adidas offer sports

shoes with sensor cavities under the insole. The Nike+ iPod sensor developed in a collaboration between Nike and Apple (fig. 2.24) in 2006, sends the data directly to an iPod nano, iPod touch or iPhone, able to tell the user time, distance, pace and calories burned. The Adidas 1 running shoe ^{2.1E} launched in 2004, is equipped with a sensor in the heel, able to measure pressure put on the shoe and the ground, while the microprocessor at the centre of the shoe calculates the ideal amount of cushioning and is able to adjust to the correct amount. Although these systems are designed to be compatible only with specific models, users have come up with creative alternatives to how the sensor can be attached to other types of footwear (fig. 2.29), although this may reduce the accuracy of the data.



Fig. 2.24: Nike+iPod sensor

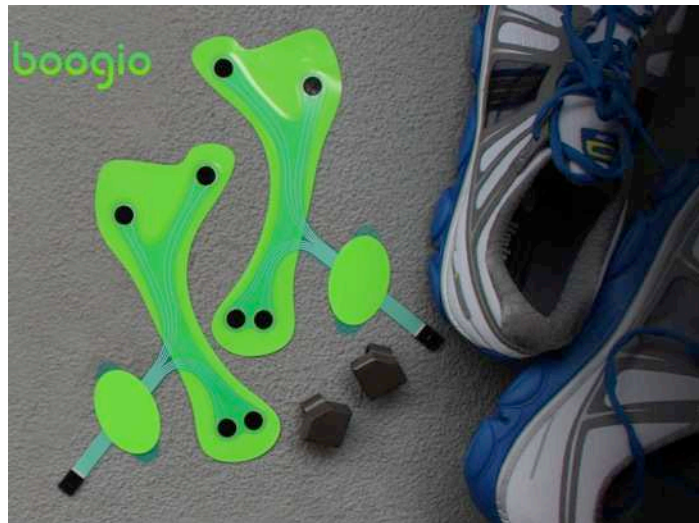


Fig. 2.25: Boogio concept artwork

In contrast to being designed to fit into particular models of footwear only, sensor-enabled insoles and attachments can be worn with many types of footwear, allowing the user to switch between running shoes, cross trainers, ski boots or ordinary footwear. Boogio Bionic Foot Sensors (fig. 2.25) can activate any ordinary shoe into a smart and interactive shoe through the use of a system that is made up from two devices; the paper-thin pressure sensor goes into the shoe, while the Bluetooth module is attached to the side of the shoe. The concept is still in development but available for pre-order and the first release of developer kits are expected to ship in 2015.



Fig. 2.26: Fitbit tracker attached to bra



Fig. 2.27: Shine attached to shirt

Fitness and activity trackers (section 2.1.5) are relevant to the research in order to study how they are worn, as manufacturers generally recommend specific wear positions to provide accurate data. Fitbit One should be worn in a pocket, clipped onto a pocket or waistband or clipped on a bra or vest (fig. 2.26), while the Misfit Shine (fig. 2.27) can be attached to any clothing or worn in the supplied rubber wristband. Nike's FuelBand (fig. 2.28) is designed as a wristband and only tracks hand movement, and is therefore not suited to tracking activities like cycling and spin classes. As documented on several blogs and discussion forums, some users have been frustrated with the restrictions on body placement and tracking parameters imposed by the manufacturers and have therefore started to experiment with alternative on-body positions on a range of tracking devices (fig. 2.28 and fig. 2.29)



Fig. 2.28: Nike FuelBand attached to laces



Fig. 2.29: Nike+iPod sensor position

2.1.3 Wearable sensors: Body or skin as the sensor carrier

These types of wearable sensors have the advantage that they are entirely independent of conventional textiles or clothing and can be worn on particular parts of the body or directly on the skin, which could provide cheaper and easier ways to wear devices, which also do not need to be washed. Especially in the healthcare & medical domain, many of these types of devices are designed to be disposable, while others are reusable, depending on the application, wear frequency and on-body location.

Body-worn

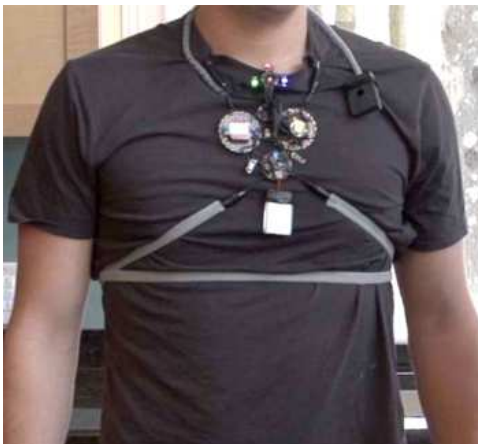


Fig. 2.30: Pollution monitor

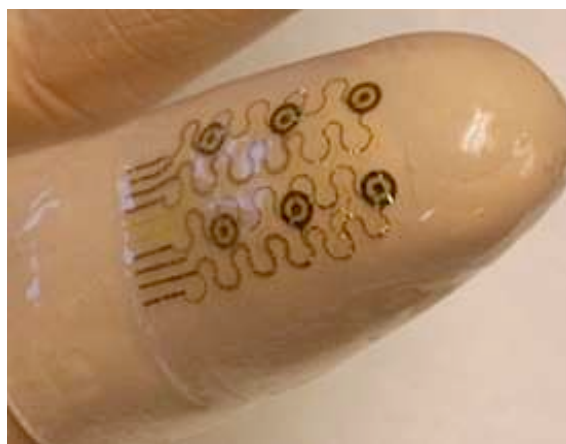


Fig. 2.31: Electronic finger cuff

In addition to wristband-based activity trackers, there are other parts of the body that can be utilised for wearable sensing, depending on the location of the stimuli (data to be sensed) and these can be clipped on, strapped on or worn on a particular part of the body. The Conscious Clothing system (fig. 2.30) is a real-time wearable air pollution monitor and breathing analysis tool that calculates the amount of polluted air a person inhales. This system was the winning design for the My Air, My Health Challenge ^{2.1F}, awarded by the U.S. Environmental Protection Agency, the National Institutes of Health and the Department of Health and Human Services. The design utilises straps worn around the wearer's chest and ribcage in combination with a number of sensors, in order to measure breath volume and pollution that is breathed in by the user. The concept of the artificial finger cuff was published by researchers from the University of Illinois at Urbana-Champaign, Northwestern University and Dalian University of Technology (Ying *et al.*, 2012), who developed an electronic finger cuff (fig. 2.31), which integrates ultrathin and stretchable silicon-based electronics, sensors and actuators into artificial skin, in order to demonstrate that

this type of artificial skin could be wrapped around other parts of the body to provide advanced tools to diagnose and treat a variety of diseases.



Fig. 2.32: Jabra sensing headphones

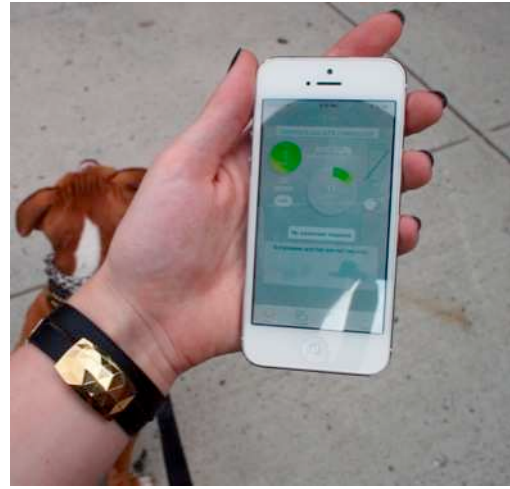


Fig. 2.33: June UV exposure bracelet

Another way to provide wearable sensing is to integrate sensory functionality into accessories that are already worn for functional or aesthetic reasons, such as headphones or jewellery. Jabra's wireless sports headphones (fig. 2.32) provide integrated heart rate monitoring by utilising its position in the inner ear, while Netatmo's June bracelet (fig. 2.33) senses and measures sun exposure through integrated UVA and UVB sensors, before an app provides the user with data in real time, so steps for adequate sun protection can be taken.

Skin-worn

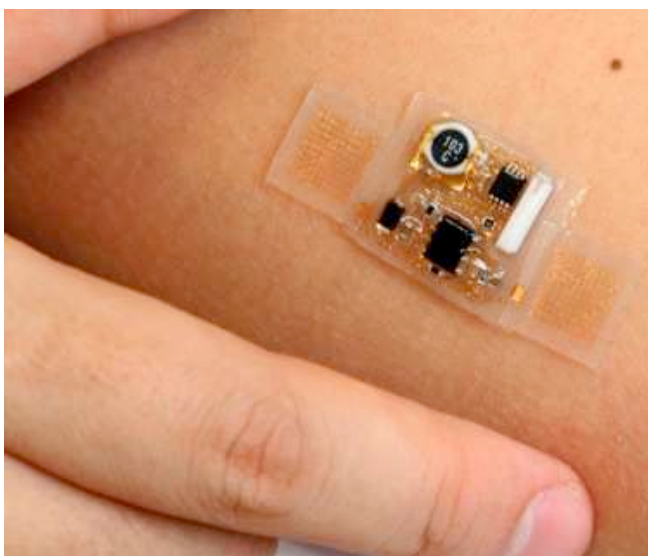


Fig. 2.34: Stick-on sensor patch



Fig. 2.35: Adhesive sensor plaster

The latest and most versatile types of wearable sensors are patch-like, plaster-like or tattoo-like devices, which do not require integration into textiles, garments or accessories, as they are adhesive and designed to be worn directly on the user's skin. The stick-on sensor patch (fig. 2.34) developed by John A. Rogers of Illinois and Yonggang Huang of Northwestern University in 2014 ^{2.1G}, incorporates electronics for wireless health monitoring and is soft and flexible in order to move with the skin, while the X Patch (fig. 2.35) developed by X2 Biosystems in 2013, is worn on the skin behind the ear to detect potential concussions during contact sports.



Fig. 2.36: Proteus Biomedical monitoring



Fig. 2.37: Prometheus Biomedical sensor-enabled pill

Although electronic pills reach beyond the general understanding of what constitutes Wearable Technology, it is important to acknowledge more futuristic approaches to on-body sensing and these include sensing devices that are carried *inside* the human body. Taking patch-enabled sensing to the next level, Proteus Biomedical, Inc. has developed a monitoring system, which includes sensor-enabled pills (fig. 2.37), adhesive body-worn stickers and an app (fig. 2.36). The patch decodes the ingested pill's signals, which are relayed to a user's smart device or healthcare professional and this system is capable of monitoring physiological information such as heart rate, motion, activity, temperature and sleeping patterns.

2.1.4 Emerging and future material substrates

Due to the explorative nature of this research project, this section presents emerging material developments from related sectors, such as flexible, plastic and printable electronics, as these could have a significant impact on design and

development of future wearable sensing substrates. Although many of these materials would not currently be considered as textiles, this research further explores what 'wearable materials' could constitute in the future (chapter 6).

Flexible & plastic electronics

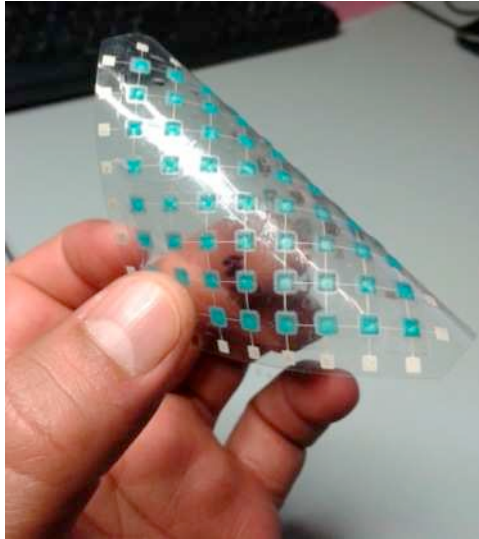


Fig. 2.38: Touch sensors on flexible foil

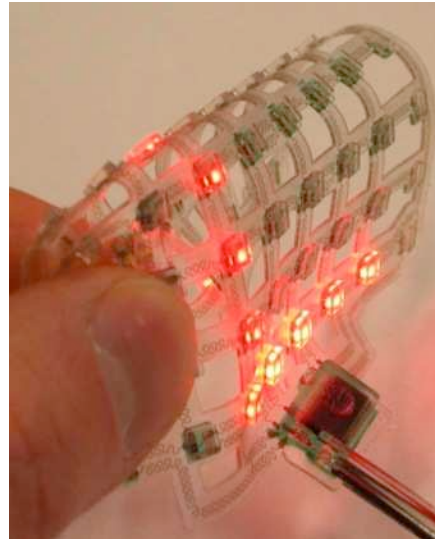


Fig. 2.39: LED enabled stretchable electronics

Flexible and plastic electronics, also known as organic or printable electronics ^{2.1H}, are a technology that is predicted to change the way electronics are manufactured and subsequently used by the consumer. The fact that electronics and circuits can be printed directly onto a diverse range of both rigid and flexible substrates, unlocks opportunities for an exciting new generation of innovative consumer products, that can be produced at lower cost, while achieving stretchability, comfort and improved performance. Due to the exciting potential of this new class of electronics for low-cost and disposable flexible sensing applications, the UK's Engineering and Physical Sciences Research Council (EPSRC) granted £1.07 million of funding to support the creation of ultra-flexible and tactile substrates in 2014 ^{2.1I}. The particular focus is on tactile skin for robotics and touch-sensitive prosthetics, which can be screen-printed on flexible foil (fig. 2.38). In terms of wearable sensing, washability is an important factor and the TFCG Microsystems Group of IMEC, based in Belgium, has been developing and testing stretchable electronics, which were shown to withstand two consecutive domestic washing cycles, while demonstrating that wearability could be enhanced through the integration of breathable zones (Vanfleteren, 2012), as shown in the LED enabled sample above (fig. 2.39).

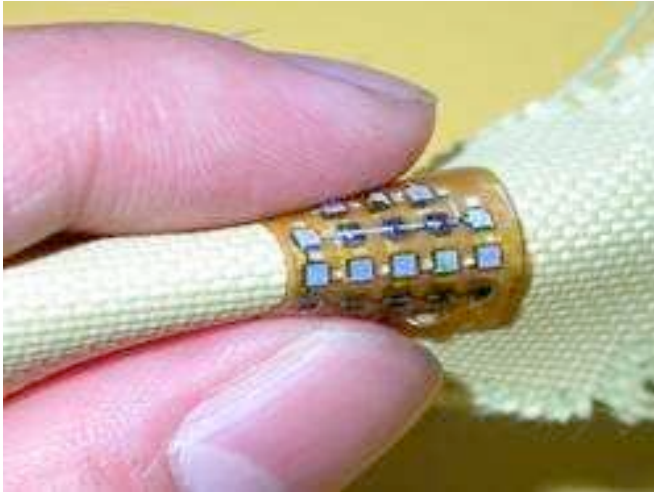


Fig. 2.40: Flexible silicon skin stitched onto fabric



Fig. 2.41: Stretchable electronics

Another research focus is on how to combine these new types of flexible electronics with traditional textiles and research at Wayne State University's College of Engineering produced a silicon flexible skin stitched onto the surface of a piece of Kevlar fabric (fig. 2.40), utilising conductive yarns (Wayne State University, no date), while the interactive Klight dress, developed as part of the STELLA project ^{2.1D}, which investigated stretchable electronics for large area applications, employed a simple thermo transfer printing process to integrate the stretchable electronic system with the textile (Lamontagne, 2015). This development also demonstrated that further protection of the electronic components is possible through adding another encapsulation layer on top, in order to improve washability (fig. 2.41).



Fig. 2.42: Epidermal electronics



Fig. 2.43: Electronic tattoo

At their most extreme, these flexible electronics can be created to mimic the skin, with properties such as the ability to bend, wrinkle and stretch, and are able to conform to the surface of human skin comfortably. They are often referred to as 'epidermal electronics', 'electronic skin' or 'electronic tattoo' and can be wrapped

around and attached to many types of surfaces, including body parts and internal organs. Research led by John A Rogers ^{2.1J} at the University of Illinois demonstrated the tattoo-like concepts (fig. 2.42 and 2.43) through the use of various electronic components, including sensors, wireless antennas and solar cells, which were mounted on ultra-thin, rubbery and water-soluble substrates to be applied to the skin with water in the same way that temporary tattoos are applied. In a commercial context, these materials are currently being explored by two companies to come out of the original academic research; MC10 ^{2.1K}, who are leaders in developing flexible and stretchable substrates for health and fitness applications and Electrozyme ^{2.1L}, who focus on epidermal sweat sensing devices (section 2.1.5).

Paper electronics & sensors

The other substrate of interest is paper, which is hailed by many experts as a promising material for the exploration of applications for printed electronics. Andrew J. Steckl (2013), Professor of Electrical Engineering at the University of Cincinnati, describes the advantages of paper-based electronics as lightweight, flexible, and biodegradable, as well as being adaptable and cheap. Current research and development in this area focuses on applications such as sensors, communication circuits, batteries, antennas and smart packaging and an array of innovative consumer products are poised to enter the market in the near future. Steckl's research group at the University of Cincinnati ^{2.1M} first started exploring paper-based substrates for electronics in 2008, and since then, the group has established the promising potential of paper and continues to explore a broad range of future applications.

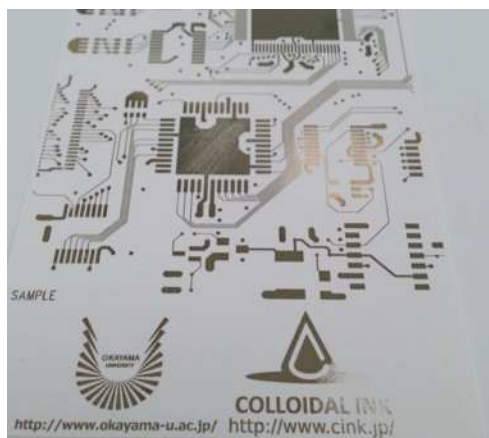


Fig. 2.44: Ink-jet printed circuit on paper

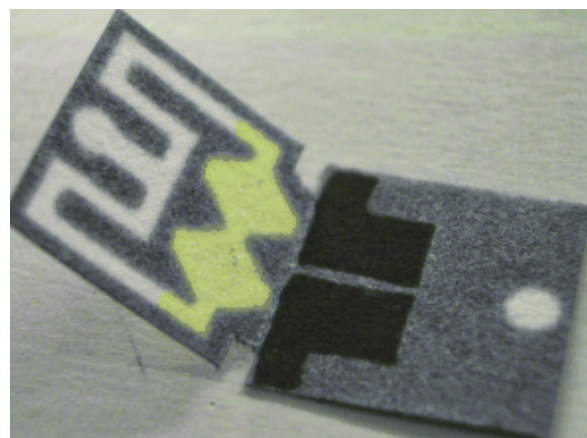


Fig. 2.45: Wax-printed paper sensor

Printed paper electronics were also a strong focus at the Printed Electronics Conference and Trade Show 2014 in Berlin, where many types of paper substrates and suitable printing technologies were on show. Arjowiggings Creative Papers showcased their ultra smooth, 100% biodegradable and recyclable paper PowerCoat^{2.1N}, which is designed as the perfect base for electronic printing, in order to add interactivity to everyday products, such as disposable labelling, tickets and packaging, while Japanese company Colloidal Ink demonstrated the use of their conductive nano inks, utilising a basic home printer (fig. 2.44) for printing on paper-based substrates.

Further to general paper electronics, much of the current research specifically focuses on opportunities for low-cost, paper-based sensing devices, which can detect stimuli both from the wearer and the environment and a particular focus is on developments for simpler, more convenient and immediate point-of-care diagnostics, both in developing and developed countries. These types of paper-based biosensors can be manufactured by utilising inkjet, wax or screen-printing, which allows in-situ fabrication even in remote areas with limited resources (Paroloa and Merkoci, 2012). In 2012, researchers at the Georgia Institute of Technology developed a prototype low-cost, paper-based wireless sensor^{2.10}, which is printed on paper or paper-like material utilising standard inkjet technology, to create sensors that can detect explosive devices. This sensor is part of a series of wireless devices, which use printed carbon nanotubes to achieve high sensitivity to ammonia. Another concept is the wax-printed sensor (fig. 2.45) developed by researchers from the University of Texas at Austin and the University of Illinois at Urbana-Champaign in 2012 (Liu *et al.*, 2012), which is highly suitable for diagnostics and elements including reagents and conductive electrodes are printed on one side of the paper and folded up and laminated, before it is ready for use.

2.1.5 Sensing applications for Wearable Technology

In line with the broad field of products, applications and evolving technologies, there are many interpretations of what constitutes Wearable Technology, which in general is considered an umbrella term to describe portable and wearable devices such as mobile computers, wearable computers and smart garments and accessories, i.e. products that display interactive functionality, such as the ability to measure, interact or react with the wearer and the environment (Cleland, 2012). Ahadome (2012),

senior analyst at IMS Research, a UK based supplier of technology market research and consultancy, described these types of devices as products that are worn on the user's body for an increased period of time, while contributing to an enhanced user experience through integrated circuitry, wireless connectivity and a certain level of autonomous processing capability. Within the context of this project, Wearable Technology comprises clothing, footwear and accessories that can be worn on or around/ near the body and are enabled by electronic elements and circuits in order to provide a specific user experience.

With a view to sensing applications, electronic wearable sensors can provide feedback on a diverse range of stimuli, these include biochemical (i.e. sweat/ pH, lactate, oxygen, glucose), physiological (i.e. ECG, EEG, temperature, respiration, skin properties), biomechanical (i.e. motion, gesture, movement, muscle contraction, acceleration, vibration), chemical & environmental (i.e. VOCs/ pollution, EMR, radiation, bacteria, vapour, smell, temperature, position, movement) and deformation (i.e. pressure, impact, touch, stretch, wear, abrasion). Many of these applications have already been researched extensively within the academic, conceptual and commercial realm and a selection of examples are presented in this section. These examples are by no means exhaustive, as new research and developments emerge almost on a daily basis, but are intended to illustrate the most significant trends for the particular period between 2005-2015.

Significant developments have taken place in this period and it is widely accepted that the growing interest in this field can be directly linked to innovation in computer and communication technology (Textiles Intelligence, 2012) and it is indisputable that the growth of the Wearable Technology market has been strongly driven by the smartphone revolution. Initially smartphones were considered a threat to Wearable Technology, as some of the functions could potentially compete, however, the first signs of a more positive view on how smartphones could affect the industry were discussed at the Wearable Technology Conference in Munich in January 2012. Keynote speaker Professor Paul Lukowicz, from the German Institute of Artificial Intelligence, remarked that the smartphone had enhanced the public's acceptance of the notion of carrying an electronic device, and instead of making wearable systems obsolete, had paved the way for Wearable Technologies to take further what the smartphone could not offer by itself (Lukowicz, 2012). Echoing these comments, VP Wearable Sports Electronics at Adidas, Stacy Burr, opened the Smart Fabric Conference in Miami in April 2012, by talking about Wearable

Technology innovation in combination with the smartphone, pointing out the great opportunities for tapping into smartphones as controllers and interface devices, thus potentially making the design of Wearable Technology simpler (Burr, 2012).

Since then, researchers, innovators, designers and entrepreneurs have embraced the relationship between Wearable Technology and the smartphone, which can act as an information hub and interface, as it is able to connect wirelessly with an increasing number of wearable devices as part of a wider ecosystem. A key factor has been the remarkable rise of mobile apps (software applications that enable various wireless computing devices including smartphones and tablet computers to provide additional services, features and functions), which in connection with products such as smart shirts and activity trackers can offer the wearer a more diverse user experience. In particular view to sensing applications, the use of the wirelessly connected smartphone as an interface, controller, data visualising and management tool and power supplier is providing new opportunities to create clothing, accessories and footwear with more features and benefits, while reducing the need for complicated embedded or integrated electronic networks within the product.

The domain of Wearable Technology is generally divided into two sectors; consumer and specialist applications, which can be further broken down into five distinctive categories; lifestyle & fashion, sport & fitness, health & wellbeing, healthcare & medical and military, space & industrial and all of these categories utilise wearable sensing technologies to produce a diverse range of research, conceptual and commercial products.

Lifestyle & fashion



Fig. 2.46: Touch-sensitive embedded joystick



Fig. 2. 47: Touch-sensitive buttons

Wearable sensor-enabled products in the lifestyle & fashion category have been driven by new technological opportunities for the integration of entertainment, information and communication features. Following the launch of the Philips/ Levis ICD+ jacket in 2000, often described as the first commercially available electronics garment, clothing and accessories with integrated and portable entertainment technology became a popular feature for snowboard and ski clothing as information and communication technologies can enhance safety and user experience, a feature which is often referred to as 'infotainment'. The North Face utilised Fibretronic CONNECTEDwear™ technology to enable several jackets in 2009, which featured embedded touch-sensitive joystick controls (fig. 2. 46) for iPod/ Audio players and mobile phones and several other snowboard brands offered jackets and accessories, such as backpacks and gloves, with built-in touch and pressure-sensitive interfaces, when iPods and mobile phones became ubiquitous products.

This trend also spilled over into fashion sectors, and in 2007, Marks & Spencer offered a line of business suits (fig. 2.47), which utilised ElekTex® integrated smart fabric touchpad technology, in order to control the wearer's MP3 player and mobile phone. While these types of touch-responsive sensing applications were reasonably successful as niche products between 2002 and 2009, their mainstream adoption was first hindered by the high cost of sensor integration and later by the technology changes in music players/ mobile phones and the mainstream adoption of smartphones. These products soon became victims of technology obsolescence, as smartphones and operating systems are constantly updated and wireless

technologies became available, which resulted in incompatibility between existing sensor-enabled garment integration systems and the latest generation of mobile devices.



Fig. 2.48: Mood-responsive fashion



Fig. 2.49: Mood-responsive clothing

Wearable sensors have also been utilised to create garments and accessories with integrated gesture control and mood and emotional response. One of the first wearable examples of gesture control was the Hug Shirt, designed and developed by CuteCircuit in 2004 ^{2.1P}. The shirt allowed users to exchange the physical sensation of a hug remotely, thanks to embedded sensors that feel the strength of the touch, the skin warmth and the heartbeat rate of the sender and actuators that recreate the sensation of touch, warmth and emotion of the hug to the shirt of the recipient. The Bubelle Dress (fig. 2. 48) is an example of incorporating emotional aspects into the design of fashion and with this project in 2006, Philips Design, a multi-disciplinary and diverse innovation team, probed how a garment could respond to subtle triggers like sensuality, affection and sensation by integrating biometric sensors that pick up the wearer's emotions to project them onto the textile in colour ^{2.1Q}. Berlin University of the Arts design student Max Schäth's concept Outsourcing, was part of an interactive fashion project in 2009 and utilised shape memory alloy and integrated sensors in the hood of the jacket to adapt shape and surface pattern in response to changes in the wearer's mood (fig. 2.49).

Sport & fitness



Fig. 2.50: Sensing sports bra



Fig. 2.51: Sensing compression shirt

The sports & fitness category has witnessed dramatic growth driven by devices and garment integrated developments that provide sensor-enabled performance analysis, maximised performance training, optimised fitness coaching and motivation and injury prevention and rehabilitation. Sports data logging is a rapidly growing trend and the design, development and use of physiological monitoring systems in sports is expected to increase in the coming years, as the ubiquity of the smartphone and its surrounding ecosystem of connected enabling technologies and apps, will further provide exciting possibilities to enhance user experience, performance and safety during sporting activities. Inspired by early developments in the healthcare and medical industry such as chest belts and bands and the first generation of commercially available smart shirts, including the Sensatex Smartshirt^{2.1R} and Vivometrics LifeShirt^{2.1S}, launched in 2000 and 2002 respectively, more recent developments comprise a variety of sensor-enabled shirts and bras and a plethora of wrist-worn or attachable fitness and activity trackers.

The NuMetrex sports bra^{2.1T}, launched by Textronics in early 2006, was the first specifically designed bra for women to provide a wearable heart rate monitoring system as an alternative to chest or arm strap monitors. Knitted and flexible textile electrodes performed as sensors by communicating with the WearLink transmitter, which snapped directly onto the bra, and transmitted the data to the Polar heart rate monitor wristwatch. This original design has been further developed in line with changing technologies and is still available today under the Adidas umbrella as Textronics and their NuMetrex line of heart rate monitoring apparel and electronics was acquired by the brand in 2008. The Adidas miCoach seamless sports bra (fig.

2.50) launched in 2014, is capable of transmitting data directly to a smartphone by utilising the Adidas miCoach app, so that the user can develop a personal training plan and synchronise, share and compare data online.

There have been many updated versions of smart shirts recently and these include compression shirts by Under Armour (fig. 2.22) and Polo Tech Ralph Lauren/OMsignal (fig. 2.51), introduced in 2011 and 2014 respectively. Both shirts provide instant biometric and physiological information such as breathing rate, heart rate and movements to keep the wearer updated on their performance and data can be transmitted to wireless devices such as laptops, smartphones, or tablets, for real-time feedback. Research is also being carried out into utilising sensing shirts to prevent injuries and long-term physical damage and although most of the emerging concepts for injury prevention and rehabilitation applications are still at the research and prototype stage, they already show great potential for commercial development in the sports and fitness market. A compression shirt developed by engineering students from Northeastern University in Boston is specifically aimed at cutting down on baseball injuries and the students claim that by monitoring body mechanics, pitchers could avoid serious injuries caused by fatigue and bad habits (Malik Chua, 2010).



Fig. 2.52: Nike+FuelBand activity tracker



Fig. 2.53: Misfit Shine activity tracker

In addition to technology-integrated clothing, new developments for accessories and footwear continue to come to the market, in order to provide the user with performance analysis, maximised performance training, optimised fitness coaching and motivation. The phenomenon of the activity tracker first surfaced in 2009, when

Fitbit launched their wireless fitness device for the mass consumer market. Fitbit's first model was a small plastic clip-on device, enabled by a three-dimensional accelerometer, capable of measuring data such as steps taken, calories burned and floors climbed and has seen several iterations and updated models, including the latest Fitbit Flex activity and sleep wristband. UP by Jawbone wristband and Nike+FuelBand (fig. 2.52) followed in 2011 and 2012 respectively, to further provide the sports and fitness consumer with new and simple ways to track and improve performance and progress. The Misfit Shine (fig. 2.53) is a fitness and sleep tracker also worth noting, as it has the same features as many other activity trackers aimed at the sports and wellbeing markets but is designed to aesthetically blend into the user's everyday lifestyle by utilising distinctive high-end materials and aesthetics and therefore provides more opportunities for continuous monitoring as part of an active lifestyle.



Fig. 2.54: Tracking and heating insole



Fig. 2.55: Impact sensor skullcap

Other alternatives to garment-integrated wearable sensors include insoles and accessories such as caps. The Digitsole (fig. 2.54) is an interactive insole, which can warm the wearer's feet, track how many steps they take and estimate how many calories were burned during an activity, while another example, the Moticon insole^{2.1U}, measures pressure distribution, weight, balance and motion and streams the data wirelessly to a PC for live measurements and direct feedback. In line with the importance for athlete's injury prevention, in 2013 Reebok launched their CheckLight skullcap (fig. 2.55), which integrates flexible sensors developed by company MC10 and is worn under football players' helmets and embedded with sensors to detect dangerous impacts, in order to reduce and prevent head injuries in athletes.



Fig. 2.56: Electrozyme tattoo sensor



Fig. 2.57: Sweat sensor

Wearable sweat sensing could become an important way to monitor and improve athlete's performance, as various devices and systems are currently being developed and tested. At the London Olympics in 2012, Irish track athletes tested sweat sensing devices, developed at Dublin City University, which measured the athlete's hydration levels and sent the information wirelessly to the coach's laptop or mobile phone, in order to enable peak performance (Benito-Lopez, 2010). As an alternative to garment or accessory integrated Wearable Technology, this new generation of sweat sensing devices is designed to be worn directly on the skin and are often referred to as 'lab-on-a-chip', a term which has been used since the late 70's to describe miniaturised devices that are able to integrate laboratory functions on extremely small scales.

Building on academic research at the UC San Diego, start-up company Electrozyme^{2.1V} are currently trialling their disposable tattoo-like (fig. 2.56) epidermal biosensor devices in conjunction with a Fortune 100 strategic partner, in order to commercialise and provide non-invasive methods to monitor metabolic substances from the wearer's perspiration, which indicate pH and hydration levels, electrolyte balance, muscle exertion and physical performance. Another investigation into sweat sensors is under way at the University of Cincinnati (fig. 2.57), where researchers are exploring the development and use of a sweat sensing patch, which communicates wirelessly via a smartphone app to inform the user about biomarkers, such as lactate levels, detected in their sweat during exercise (Fuller, 2014).

Health & wellbeing

There is a definite overlap between the sports & fitness and the health & wellbeing sector, as the population's awareness of the importance of health and fitness is growing steadily and consumers are increasingly exposed to the concept of

'Preventative Health', which involves the promotion of healthy living and active disease prevention. One of the key drivers of this paradigm shift to prevention has been the rapidly growing trend and subsequent mainstream adoption of self-tracking, which was first popularised by the 'Quantified Self' (QS) ^{2.1W} movement, which entails the activities of gathering, managing, analysing and sharing personal data, in order to enhance health, wellbeing and quality of life. Wearable sensing devices have an important role to play in the field of health and wellbeing, as we have been able to observe a growing number of research and conceptual projects and commercial products covering parameters such as activity levels, weight loss and motivation, sleep and nutrition, emotional wellbeing, posture and special interests such as baby monitoring and UV protection.



Fig. 2.58: Zeo sleep monitor



Fig. 2.59: The GER mood sweater

In addition to the performance oriented activity trackers highlighted in the sports & fitness section, the use of wearable monitors to assist with weight loss and healthy eating, as well as improvement of sleep quality, has become an important tool to encourage users to participate in a more healthy and preventative lifestyle. Sleep tracking is a systematic way to track sleep patterns and generate data, which easily highlights how sleep is affected by other factors such as diet, stress and alcohol consumption. The Zeo sleep monitor (fig. 2.58) was developed to enable the wearer to make the most of their sleep cycles, in order to ensure deep sleep and following its launch in 2009, transitioned into a sleep coach, as the company extended their offer to a sleep monitoring website and various mobile apps.

In addition to physical health and wellbeing, numerous research and conceptual projects also investigate how to encourage and support emotional wellbeing, considering aspects such as stress, mood swings, anxiety and depression.

Scentsory Design ^{2.1X} by University of the Arts London researcher Jenny Tillotson, utilises scent as a tool to create mental and physical wellbeing for the wearer, as integrated biosensors detect stress and activate the delivery of odorant benefit chemicals in controlled and personalised ways through the worn garment. This scent release is designed to reduce stress, boost energy, relax or improve concentration. Tillotson has been developing the research over many years and is further exploring the combination of biology with Wearable Technology to benefit people with chronic mental health conditions such as bipolar disorder. Although mood is a difficult parameter to measure, sensors can indicate the wearer's mood or emotional state through changes in sweat-induced moisture on the skin, which determines the level of skin conductance, also known as galvanic skin response (GSR). The Galvanic Extimacy Responder mood sweater (fig. 2. 59), presented by conceptual designer Kristin Neidlinger, is based on the technology of a lie detector test and uses GSR to detect the wearer's excitement levels through sensors placed on the hands, before interpreting the data instantly into an interactive display of coloured light (Neidlinger, 2013).

Poor posture at work is believed to be the major cause of back pain, workplace stress and repetitive strain injury and back pain is believed to result in about 83 million lost working days each year (Druss, Olfson and Pincus, 2002), therefore the potential to develop innovative solutions in this field are significant. Lucy Dunne, Associate Professor of Apparel Design and Wearable Technology at the University of Minnesota, addressed this issue through research into a wearable posture monitoring vest ^{2.1Y}, which is able to sense posture and provide feedback and reminders to the user, as soon as they lapse into an unhealthy position. A fibre-optic sensor is embedded into the vest to detect movement and position of the spine and the data is sent to the user via a Bluetooth connection, displaying an icon on the user's computer desktop as an alert. Another work-related issue is that of Repetitive Strain Injury (RSI), which is a major concern and cost for employers and is believed to affect over 40 million workers across the continent while being responsible for 50 per cent of all work-related ill-health (www.sciencedaily.com, 2008). The Context project by SFIT (Smart Fabrics, Interactive Textiles) therefore aimed to address serious work safety issues and developed a range of unobtrusive and reliable wearable RSI sensors that can warn wearers to take a recuperative break when necessary (Langereis *et al.*, 2007).

Interest is also growing in concepts and products addressing wellbeing during and after pregnancy, both for mothers and their babies. In 2014, Silicone Valley based start-up Bellabeat launched the Bellabeat Leaf (fig. 2.60), a wearable activity tracker, worn as a bracelet, necklace or pendant, which gives the mother-to-be an insight into both her own and her baby's health through integrated sensors. The Mimo onesie (fig. 2.61) is equipped with integrated sensors to measure the baby's skin and body temperature, breathing and movement, and the data and live audio is relayed via the cloud to the parents' connected smart devices.



Fig. 2.60: Bellabeat Leaf baby monitor



Fig. 2.61: Mimo baby monitor

Healthcare & medical

Diverse garment and accessory integrated sensing technologies contribute to both physical and emotional wellbeing by providing feedback on chemical biomarkers, posture, mood, anxiety and depression, as the health & wellbeing category merges almost seamlessly into the healthcare & medical sector. Research, developments and products in this sector offer risk assessment and diagnosis and disease detection, monitoring and management, but are generally subject to US Food and Drug Administration (FDA), CE (mandatory marking for specific products sold in the European Economic Area) or other international certifications, in order to provide medical care safely and appropriately.



Fig. 2.62: Georgia Tech 'Smart shirt'

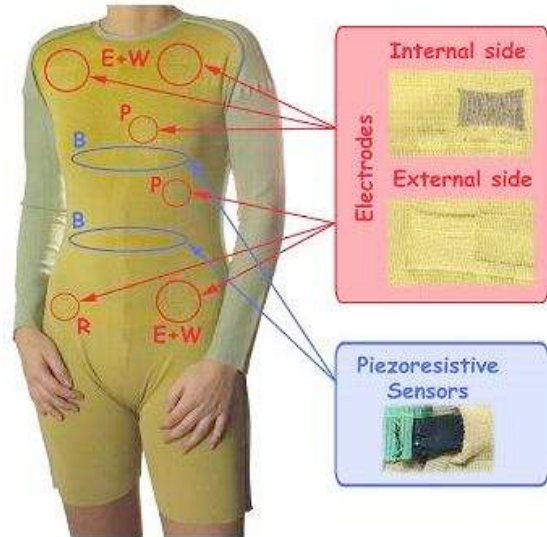


Fig. 2.63: WEALTHY project

Since the development of Georgia Institute of Technology's original 'Smart shirt' (fig. 2.62) from 1996-2000^{2.1Q}, which contained sensors to monitor vital signs such as heart rate, EKG, respiration and blood pressure, various interpretations have been developed over the years. In the medical healthcare and medical sector, examples can be found both in the research and the commercial domains, as physiological monitoring, such as heart rate, ECG, breathing rate, body temperature and biochemistry, has been a focal point for the development of risk assessment and diagnosis applications. Notable projects include the WEALTHY project (fig. 2.63), supported by the 5th Framework IST Programme of the European Union running from 2002 to 2005, which utilised sensors to monitor physiological variables like respiration, ECG, activity, pressure and temperature and the follow-up project MyHeart, which investigated approaches to fighting cardio-vascular diseases by providing the user with garment-integrated monitoring and early diagnosis (CSEM, 2010a).



Fig. 2.64: Artificial pancreas system

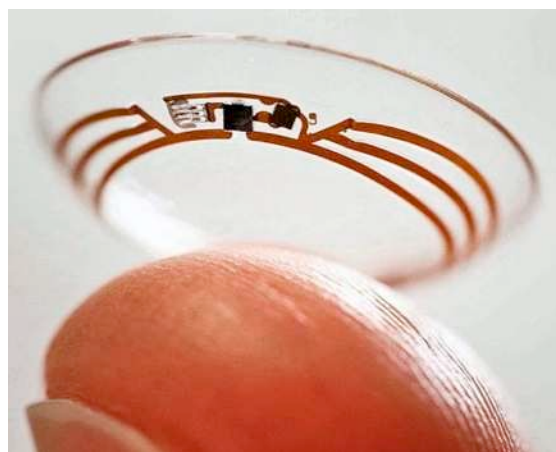


Fig. 2.65: Smart contact lens

Products for disease monitoring and management cater for conditions such as diabetes, Alzheimer's and heart-related diseases and provide the user with the opportunity to be in control of their own health and continue to live an active and independent life, while reducing healthcare costs. In addition to conventional clothing and accessories, a new type of wearable has been emerging over the last couple of years; sensor-enabled adhesive patches and plasters that are worn directly on the skin and are easy to wear and can be concealed under clothing and worn during many activities including sports and swimming. These include the SensiumVitals patch^{2,12}, a single-use, disposable wireless device, which offers continuous monitoring to track heart rate, respiratory rate and axillary temperature and the 14-day wearable Zio patch from iRhythm Technologies, which is a cardiac rhythm monitor that is specifically designed to capture irregular heart rhythm to diagnose potential arrhythmias in patients (Ouyang, 2014).

Diabetes is now considered a disease with epidemic proportions and the cost of treatment is a major burden on global health authorities, so the growing interest and development activity in body-worn drug delivery systems is not surprising. The Pancreum wearable artificial pancreas system (fig. 2.64) detects, manages and regulates the wearer's glucose level with limited input from the user. One of the latest concepts for wearable diabetes devices is Google's smart contact lens (fig. 2.65), which is capable of sensing and measuring blood glucose levels contained in human tears. If brought to market, this device would monitor the patient's blood sugar on a second-by-second basis and Google are in the process of developing the prototype in discussion with the FDA and various technology partners, to launch the product to the market in the near future (Lanxon, 2014).

Military, space & industrial

Although the military, space & industrial category is a specialist, highly technical and advanced niche market, developments in these segments are likely to roll out to the healthcare & medical and consumer sectors, once the technologies have been tried and tested and are affordable and feasible in a commercial context. Key applications originally developed for this specialist market have already made an impact in the consumer segment and include physiological and environmental sensing and heating and cooling technologies as well as initial developments for energy harvesting and management.



Fig. 2.66: YDreams firefighter suit



Fig. 2.67: ProeTEX t-shirt

Portuguese company YDreams developed a firefighter suit (fig. 2.66) for the European Space Agency (ESA) and this suit provides full body protection, is equipped with GPS and fitted with body sensors to provide information about the health status and position of the fire fighter to the team leader and the coordination centre via a communication chain (ProeTEX, 2009). A similar example by ProeTEX (2006-2010), focused on developing textile and fibre based integrated smart wearables for emergency disaster intervention personnel. The project aimed to improve emergency safety, efficiency and coordination by providing workers with wearable sensing and transmission systems that monitor their health, activity, position and environment. Prototypes consist of a t-shirt with a heartbeat, breathing and temperature sensor (fig. 2.67), a jacket with a temperature sensor, accelerometer, data processing unit and textile antennas for communication and boots with an integrated gas sensor (*ibid.*).

2.2 Non-electronic wearable sensors

Although in the context of Wearable Technology, sensors are generally associated with the use of electronics, this section investigates potential opportunities for the design of future wearable sensors for Preventative Health, by considering a more low-tech approach, including stimuli-responsive textiles and materials that can provide visual response to stimuli from the wearer or the environment without the use of electronic elements and power. The examples presented in this section can be viewed as a very simple form of smart textiles, as they display what Associate

Professor of Materials Science and Engineering at the University of Illinois, Shim, refers to as '*surface reactive properties*' (2013, p. 92). This means that a textile or material can sense and react to a stimuli based on a range of surface treatments (such as printing and dyeing), which can be imparted to the textile's surface in order to provide sensory functionality.

The non-electronic wearable sensors presented in this section include clothing and accessories from the realm of fashion and sportswear, as well as examples from the field of diagnostics, which can provide simple visual feedback (such as colour and pattern change), in order to visualise a valuable response to selected stimuli or are capable of collecting body fluids to be analysed away from the body. Most of the diagnostic examples presented here are handheld/ portable and not currently wearable but they provide important references as they could provide inspiration to create wearable versions in the future.

2.2.1 Fashion & sportswear textiles

Textiles and garments can react to factors such as body heat, temperature, UV light, water, acidity levels and pollution, through the use of various inks and dyes, including thermochromic, photochromic and hydrochromic pigments.

Colour & pattern change

Visual effects including colour and pattern change have long intrigued designers and there are many examples of textiles that change their appearance in response to body heat, sunlight, water or other environmental factors, such as pollution and acidity levels in rainwear.



Fig. 2.68: Heat-responsive fashion



Fig. 2.69: Heat-responsive sportswear

One of the most commercially successful colour-change fashion crazes, was the Hypercolor t-shirt ^{2.2A}, first launched in the early 90's, which utilised a combination of regular and thermochromic dyes and responded to the wearer's body heat by fading to a paler colour. This principle has since inspired many followers, most recently Alexander Wang, who produced his colour-changing Autumn/ Winter 2014 catwalk collection (fig. 2.68) by utilising heat-sensitive inks on a range of materials.

In 2007, MA Textile Futures student Kerri Wallace from Central Saint Martins, University of the Arts London, presented her collection 'Motion Responsive Sportswear' ^{2.2B}, which utilised a combination of thermochromic and thermochromic liquid crystal inks, to enable the visualisation of heart rate and body temperature through colour change of the garments. In an almost identical approach, US company Radiate Athletics attempted to commercialise colour-changing sportswear in 2013, by crowd-funding a collection of workout clothing that changes colour according to body heat and in order to show off the active muscles (fig. 2.69).



Fig. 2.70 Swine flu mask with pattern enabled warning system

Thermochromic, photochromic and hydrochromic inks can also be used to create changing, fading, appearing or disappearing coloured patterns, in response to heat, UV light and water respectively. Thermochromic inks were used for the swine-flu masks (fig. 2.70) created by Swedish textile student Marjan Kooroshnia, in order to provide full-face protective sinus masks, which further detect temperature increases around the forehead or mouth, while UK company Squid London create rain-

responsive umbrellas and rainwear ^{2.2C}, which change from a monochrome design with white motifs, to a multi-coloured pattern, when exposed to rain.



Fig. 2.71: Environment-responsive fashion



Fig. 2.72: Rainwater-responsive clothing

THE UNSEEN's collection 'Air' (fig. 2.71), first presented in 2014, utilises bespoke inks and dyes that respond to a variety of biological and chemical stimuli found in the air, including pollution, moisture, UV light, chemicals, friction and temperature and each element has a different colour-changing effect to visually inform the wearer of changes in the environment. The collection's London-based designer Lauren Bowker is keen to point out that her clothing should not be considered as Wearable Technology but is simply an example of material innovation (McDonald, 2014). In 2012, MA Textile Futures student Dahea Sun from Central Saint Martins, University of the Arts London, developed a set of dyes that can respond to the acidity levels found in rainwater. Sun's 'Rain Palette' dyes were created with water-soluble pigments found in red cabbage and blackberries, and were utilised to create a collection of garments that could visualise air quality through rainwater (fig. 2.72). Furthermore, the concept explores the potential for the wearer to record and upload rain pH readings online, in order to create a global database of real-time environmental data.

2.2.2 Diagnostics

The most well known types of low-tech diagnostics are the pregnancy test, blood-sugar level strips and pH litmus test, which respond to particular human biomarkers found in urine and blood. Furthermore, a number of body fluids including blood, urine, saliva and sweat can be used as diagnostic biomarkers to detect a diverse

range of health disorders, conditions and threats such as infectious diseases, while environmental diagnostics include the testing of water and gases.

Colour change

Paroloa and Merkoci (2012), consider the invention of chromatography by Martin and Synge, who were awarded with the Nobel Prize in chemistry in 1952, the first paper-based sensor. Paper chromatography is a scientific but simple analytical technique, which is used to separate and identify individual parts of a mixture and only requires very small amounts of the mixture. In the context of the body, paper chromatography can be used to test for pregnancy, pH levels, which can indicate diverse aspects of human health and blood-sugar levels, which are important for people with diabetes. Pregnancy tests are used for home testing to determine if a woman is pregnant or not, and the user has to urinate on chromatographic paper enclosed inside a plastic case, while pH tests (fig. 2.73) respond to urine and saliva to indicate whether the user's pH levels are acceptable or need attention. Diabetes sufferers need to undertake regular blood and urine tests to establish their blood sugar levels but only urine tests work on the principle of chromatography to give instant feedback via colour change of the test strip.



Fig. 2.73: pH level test strip

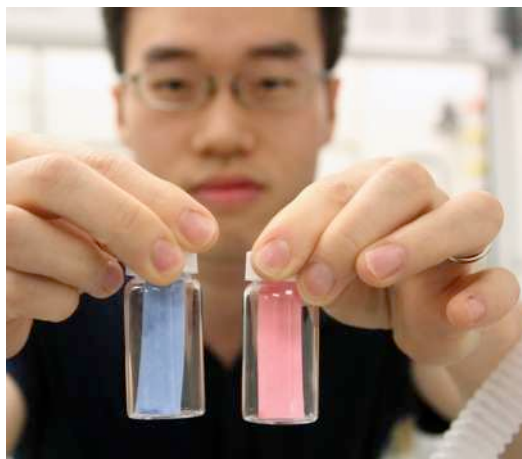


Fig. 2.74: Paper litmus test

Litmus tests are mainly used to determine whether a solution or gas is acidic or basic, however wet litmus paper can also be employed to test water-soluble gases, such as ammonia, chlorine and nitrogen and researchers at the University of Michigan have developed a low-tech diagnostic test (fig. 2.74) for nerve gases, which are normally colour, odour and tasteless and can threaten soldiers' lives in combat. These paper strips are designed to change colour within 30 seconds to indicate exposure to any traces of dangerous nerve gas^{2.2D}.

Fluid collection



Fig. 2.75: Origami-inspired glucose sensor

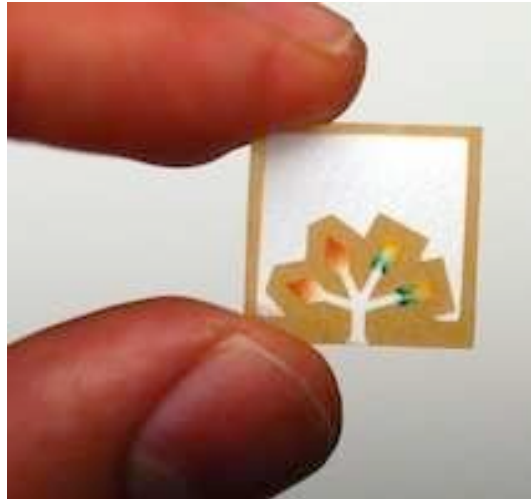


Fig. 2.76: Paper based glucose sensor

Another low-tech approach to diagnostics and biosensing are microfluidic devices, which utilise paper's natural wicking ability to collect and transport liquids in combination with applied (i.e. printed, cut, etched) hydrophilic channels and hydrophobic barriers. The potential of these types of devices is currently being explored and developed by numerous research groups around the world, as they are considered to potentially provide low-cost, self-contained, disposable and easy-to-use diagnostics in the future. One of these projects is a 3-D, folded and origami-inspired paper sensor (fig. 2.75) developed by chemists at The University of Texas at Austin ^{2.2D}, which can test for diseases like malaria and HIV and could provide feedback by turning a specific colour. The innovators have also engineered a way to run more complex tests that require power, by adding a simple battery. The microfluidic glucose sensor (fig. 2.76), developed at Whitesides Group Research at Harvard University ^{2.2E}, is made from paper and a water-repellent polymer and can be used to detect biomarkers from body fluids such as blood, urine and saliva. After dipping the device into the body fluid, the liquid is wicked up through the channels until it reaches a reactive compound and changes colour. An imaging device could then digitise the results to transmit them to an expert, who interprets them to respond with a suitable treatment.

2.3 Summary and conclusion

In order to provide a broader scope for innovation, the research distinguishes between *electronic* and *non-electronic* wearable sensors. Electronic wearable

sensors comprise clothing, accessories or footwear made from electronic, sensor-enabled textiles and materials, or clothing, accessories or footwear made with integrated or attached sensing elements. These types of wearable sensors display various degrees of integration, which comprise the textile, clothing or the body or skin as the sensor carriers. Non-electronic wearable sensors include clothing and accessories from the realm of fashion and sportswear, as well as examples from the field of diagnostics.

In regard to applications for wearable sensors, the review further highlighted the emergence of the health & wellbeing category, which provides devices that enable the user to take an active role in participating in healthy living and disease prevention and new wearable sensor concepts could contribute to further meaningful innovation in this field. Specifically, the review identified three degrees of sensor integration, and the emerging approach of non-integrated sensing devices, which can be attached to existing clothing, accessories or footwear, or worn on specific parts of the body, or directly on the skin, is of particular promise for this research. Another key element of the review is the identification of emerging and future material substrates from related sectors, which could provide useful inspiration for the design of innovative new wearable sensor concepts in the future.

This contextual & literature review presented an abundance of inspiring academic, conceptual and commercial research and developments for wearable sensors, as well as emerging areas of interest. Judging by the unprecedented growth in research activity in the field of sensor-enabled, textile-based Wearable Technology, promising design opportunities for wearable sensors are undeniable and a selection of opportunities are presented and discussed in chapter 3.

Chapter 3: Design opportunities for wearable sensors

Despite predictions of significant growth for the next generation of Smart Clothing and Wearable Technology (PRWeb, 2013; IMS Research, 2012) and the current hype and commercial product launches in the sports & fitness and health & wellbeing categories, the market has been slow at realising its potential, beyond the success of relatively expensive and potentially short-lived gadgets. It is therefore essential to remain critical of academic, commercial and conceptual developments by probing some of the more significant obstacles, which may be holding back innovative and successful developments of textile-based Wearable Technology.

In order to stimulate the design of wearable sensor concepts, this research identified and studied a range of challenges in the broader field of Wearable Technology, which includes textile-based as well as hardware products. The report 'Wearable Technology: Issues and challenges across the lifecycle stages' (Prahl, 2012, appendix A), which I wrote as part of my initial contextual and literature research during the early stage of the project, suggested that there are many issues and concerns around the design, development, manufacture, sales, use and end-of life of textile-based Wearable Technology. These include specific practical issues, such as the lack of comfort and desirable aesthetics suitable for different user tastes and preferences, frustrations around unsuitable interfaces and problems with wash care and power supply and storage. Broader challenges range from missed opportunities around innovating in response to genuine and identified user needs, a distinct lack of essential multidisciplinary collaboration during the design, development and manufacturing stages, complications brought on by built-in obsolescence due to constant software and technology upgrades and concerns about data security and privacy. Furthermore, it became evident that unlike the textile & clothing industry, stakeholders involved in the design, development, production and sales of Wearable Technology (including hardware and textile-based products) are reluctant to consider any potential negative environmental (i.e. resource depletion and pollution) and human impacts (i.e. potential health hazards to workers and end-users) their commercial products could cause during manufacture, use and end-of-life.

The research brings together emerging fields of interest (design for Preventative Health and the exploration of non-integrated wearable sensors) with current challenges occurring during the design and development of hardware and textile-

based Wearable Technology design (the lack of consideration for environmental issues with a particular focus on the product's end-of-life and the industry's often criticised tendency to settle for product innovation following the technology push model). This chapter discusses these critical observations in view of turning them into design opportunities, which provide the framework for the project in line with my convictions as a professional textile & clothing design practitioner.

3.1 Designing for Preventative Health

The financial burden on global healthcare systems, caused by the rapidly growing numbers in chronic diseases and illnesses linked to the lack of activity and exercise and an increasing ageing population, has now reached unprecedented levels (United Nations, 2011; Halpin, Morales-Suárez-Varela and Martin-Moreno, 2010). In response to this pressing challenge, attention has been shifting from the traditional approach of disease management and treatment towards preventative healthcare, which sees the user's role changing from a passive to a more active one (Swan, 2012). This paradigm shift towards preventative healthcare has the potential to make healthcare systems more efficient and in response to this development, we are currently witnessing the emergence of what is often described as the 'digital health revolution', which has prompted a significant increase in research and commercial developments of specific devices, accessories and clothing. These products can offer disease detection, monitoring and management, thus empowering the user to lead a healthier lifestyle and make healthcare more effective. This research project therefore focuses on the design and development of wearable sensor concepts, which can enable the user to protect and manage their health at the earliest possible stage, thus *'acting to make health decisions well before they become patients.'* (Goetz, 2008).

Indeed, Kirstein *et al.* (2007), researchers at ETH Zurich, University for Technology and Natural Sciences, described a type of device, which could enable the user to actively engage with their health:

“The wearable health assistant could help people fight diseases by a preventative lifestyle and early diagnosis. The user could take control of their health status and adapt a healthier lifestyle. This self-management of health makes people more independent, improves their quality of life and at the same time reduces healthcare costs.” (Kirstein *et al.*, 2007, p. 254)

This approach is reflected by Coyle and Diamond (2013), key academic researchers in the domain of wearable sensing systems from Dublin University, who state that smart garments can act as a personalised healthcare solution, thus contributing to making the wearer more aware of their own health status in order to take a more involved role. Consequently, there are exciting opportunities to research, design and develop new tools, devices and services in this field and David Webster of multidisciplinary design studio IDEO describes innovating for health and wellness as *‘the defining design challenge of our time’* (Webster cited in Dick-Agnew, 2013).

3.1.1 Biochemical sensing

As documented in chapter 2, there are already many research projects and commercial developments based on the sensing of physiological measurements, such as body temperature, heart-rate, blood pressure, respiratory activity, location movement and posture. In contrast, the field of biochemical sensing detects particular human biomarkers, which are identifiable substances present in body fluids, excretions and tissues, and this particular field is still under-explored (Luprano, 2008; Morris *et al.*, 2009; Coyle and Diamond, 2013). Coyle (2007) states that on top of monitoring the wearer’s environment and detecting threats, they can be used to sense and provide valuable information on the wearer’s health status and the collaborative, EU-funded BIOTEX project explored the development of garment embedded sensors capable of collecting and analysing the chemical composition of body fluids with a particular focus on sweat, and presented wearable textile-based sensors that can measure sweat pH to provide physiological information, which could be used for applications in healthcare in the future (Coyle *et al.*, 2010). In 2011, researchers at the University of Oslo and the National

Hospital of Norway, developed a new type of sweat meter to detect low blood glucose levels in order to avoid hypoglycaemia and other conditions such as chronic fatigue syndrome ^{3A}, while researchers at MIT Media Lab in Cambridge, USA, have developed a sweat sensing wristband that could predict seizures by measuring skin conductance, in order to eliminate seizure-related serious or fatal consequences ^{3B}.

There is significant potential to explore new form factors for wearable sensors, which can detect, monitor and analyse these human biomarkers, in order to determine the health status of a human being. Of particular interest are Volatile Organic Compounds (VOCs), which are natural gases continuously emitted in breath, blood, urine and sweat. As discussed by Shirasu and Touhara (2011), researchers at the Department of Applied Biological Chemistry, The University of Tokyo, these disease-specific VOCs could be utilised as diagnostic biomarkers to indicate a broad range of illnesses and conditions, including infectious and metabolic diseases and genetic disorders, asthma, chronic obstructive pulmonary disease, tuberculosis and various types of cancers including lung, gastric, colon, skin and breast cancer. In addition to the internal VOCs produced by humans, VOCs emitted from the body can also indicate current or previous exposures to environmental VOCs (section 3.1.2), thus providing insights into the relationship between human exposure to environmental chemicals and the onset of illness and development of chronic diseases.

Ongoing research around the concept of utilising VOCs as non-invasive diagnostic tools include work by Japanese researchers from Okayama University Graduate School of Medicine, Dentistry and Pharmaceutical Sciences, Wang *et al.* (2007), who tested the possible use of unmetabolised VOCs in urine as biomarkers of low-level indoor exposure; scientific researcher on the senses of taste and smell at the Monell Center, Gallagher *et al.* (2009), who developed sampling techniques to obtain VOC profiles from the upper back and forearm skin, in order to search for biomarkers of skin diseases, and most recently, scientists Sinues, Kohler and Zenobi (2013) at ETH, Swiss Federal Institute for Technology in Zurich, who explored the potential of human breath analysis to monitor an individual's health status over a prolonged period of time. As this research is concerned with exploring the design of wearable sensor concepts, rather than looking at biomarkers in breath, blood and urine, the focus is on skin-based biomarkers, in order to probe new types of wearables that could be worn on or near the skin to collect in-situ data from the wearer. Furthermore, a compelling factor of VOC-enabled diagnosis is that skin-

based VOCs are mainly derived from sweat (Shirasu and Touhare, 2011) and it is important to note that in addition to VOCs, sweat contains further biomarkers such as lactate, oxygen, norepinephrine, glucose, amino acids and electrolytes (Windmiller, 2013). Sweat analysis can therefore provide valuable insights into a person's state of fitness, wellbeing and health, making wearable sweat sensing an excellent non-invasive tool as part of a preventative healthcare approach. This method has been utilised as an important tool for diagnosing Cystic Fibrosis for over 60 years by testing sodium and chloride concentration levels (Mishra, Greaves and Massie, 2005).

3.1.2 Environmental sensing

Until recently, most preventative healthcare research initiatives have focused on people's backgrounds and lifestyle habits, such as alcohol consumption, unhealthy diets, physical inactivity and smoking, but the authors of the recent report 'NCDs and environmental determinants' (Jensen *et al.*, 2013), emphasise significant opportunities to improve health and reduce associated health care costs, through addressing human environmental exposure. Toxic air pollutants are known to be poisonous and harmful to the environment as well as human health and inhaling these pollutants can increase the chances of experiencing serious health problems, such as cancer, respiratory irritation, nervous system problems, lung damage and birth defects (US Environmental Protection Agency, 1991). VOCs present in the environment, which can be man-made or naturally occurring gases, can be extremely harmful to human health. Adverse VOCs in the environment are present in both outdoor and indoor pollution, which includes toxic chemicals, often used in paint, furniture and cleaning products and have been identified as potential causes of non-communicable diseases including cardiovascular diseases, many types of cancer and chronic respiratory diseases (US Department of State, 2011).

Wearable environmental sensors have already caught the imagination of designers and researchers (chapter 2), as changing, fading and disappearing colours and patterns, as well as LEDs, are applied to clothing and accessories to respond to environmental stimuli such as UV light, pollution and air quality, in order to provide immediate warning and feedback for the user. While the non-electronic sensors presented in section 2.2 can only offer simple visual feedback and warning about the environment and are unable to provide scientific data, electronically enabled

sensors can provide more detailed information, which could help the wearer to make educated decisions in order to protect their long-term health and wellbeing. One such example is the Conscious Clothing system (fig. 2.30), a wearable air pollution-measuring device, which aimed to demonstrate the need for a future in which people could have more control over their long-term health outcomes by utilising affordable and portable sensors to measure the air quality around them, while receiving feedback on physiological changes, potentially caused by the environmental pollutants.

Another potential environmental issue is electromagnetic radiation (EMR), which is energy, such as radio, TV, radar and microwaves, heat and light, released during certain electromagnetic processes. Exposure to these emissions from sources such as power lines, wireless transmitters, TVs, mobile phones and microwaves is increasingly viewed as a threat to human health, although concrete scientific research to evaluate such impacts is still relatively scarce. However, growing numbers of users and healthcare professionals are becoming concerned about the impacts of mobile phone and other wireless device use and a group of European doctors have been warning their colleagues, the public, politicians and health officials about the serious health risk linked to such wireless communication technologies since 2002, as part of the Freiburger Appeal initiative ^{3C}. Physicians associated with the initiative continue to observe a clear increase in health symptoms, including chronic fatigue, headaches, migraines, vertigo, tinnitus, fluctuations in blood pressure, degenerative neurological, behavioural and learning disorders, strokes and cardiac arrhythmias, and claim that these observations are consistently and increasingly confirmed by scientific findings.

The World Health Organization (WHO) classified radiofrequency field radiation from devices such as mobile phones as possibly cancerogenic in May 2011 and their formal risk assessment of all studied health outcomes from radiofrequency fields exposure, carried out as part of the International Electromagnetic Fields (EMF) Project, is due to be completed in 2016 (World Health Organization, 2014). A growing number of devices, clothing and mobile applications designed to alert to or protect the user from potentially harmful electromagnetic radiation exposure exist already, although these currently remain niche products. In 2013, company Tawkon ^{3D} launched its cell phone radiation app, which warns users when their specific absorption rate (SAR) has reached a certain level, while in April 2015 it was announced that start-up company SQUID had released a wristband that can charge

electronic devices including smartphones, digital cameras and MP3 players, while providing real time analysis of exposure to electromagnetic radiation (PRLog, 2015).

3.2 Designing for the product's end-of-life

The need to develop creative and cost-effective solutions for issues associated with the end-of-life of clothing and textiles has been high on the agenda in the textile & clothing industry for many years, although a report released by Friends of the Earth Europe (2013) states that Europe still only recycles 25% of its textile waste, while 75% end up in landfill or are incinerated, despite the fact that 40-50% of waste textiles could be recycled into garments, 20-25% could be used as cleaning cloths, while 20 to 30% could be used by other industries as a secondary raw material, i.e. sound proofing/ insulation. In the UK, the textile and clothing design and manufacturing industry appears to be increasingly aware of the significant environmental burden that is caused by textile waste and consequently there has been a particularly strong focus on the exploration of design-driven strategies to address end-of-life issues for textile-based products. Designers have recently been working with pre-consumer textile waste such as factory waste and off-cuts, obsolete stock and surplus materials, and post-consumer textile waste, which constitutes unwanted and discarded clothing (Prahl, 2014). In addition to such textile waste management strategies, there has also been an increasing interest in developing design strategies for waste reduction and elimination as part of the concept of 'designing out' waste, and these include material waste reduction through design efficiency and construction, design for durability and longevity, design for reuse and repair and design for disassembly and remanufacture or recycling (*ibid.*). On their Clothing Knowledge Hub, which is a freely accessible tool for textile & clothing industry stakeholders to reduce carbon, water and waste impacts, UK organisation WRAP describes this approach as 'design for end-of-life', which involves planning '*...for a product's life beyond its first life, enabling disassembly, recycling and remanufacture to create new products with the ultimate aim to eliminate waste altogether.*' (Wrap, 2014).

With regard to electronic consumer products, it is well documented that the rapid growth of electronic waste, which is often blamed on shorter lifespans of electronic goods, has had a dramatic impact on developing countries, as these are often left to deal with dumped e-waste from developed countries due to loopholes in the current

Waste Electrical and Electronic Equipment (WEEE) Directives (UNEP, no date). Organisations such as Greenpeace have been publicising associated impacts of e-waste dumping for years, although producer responsibility for electronic products currently not covered under the WEEE Directive (such as electronic textile enabled clothing), appears to be non-existent, thus making the necessity to address the end-of-life impact of any products containing electronic components extremely pressing.

Eco-design for electronic products is more established than in the textiles & clothing sector, however, despite an abundance of academic research, publications and guidelines for designers of electronic and energy-related consumer goods (Sherwin, 2000; Bhamra and Lofthouse, 2007; Stevels, 2007; European Commission, no date; Tischner and Hora, 2012), there is still significant scope for innovation, development and implementation of design-driven approaches to improve electronic consumer products in regard to their impact on the environment, during manufacture, use and at end-of-life. The key areas for eco-design for electronic consumer products currently include design for recycling, the phasing out of certain hazardous substances as stipulated by the European RoHS directive and design of energy efficient products (Köhler, 2013). In line with the proliferation of smartphones, there have recently been a growing number of research projects to explore smartphone design for durability and recovery (University of Bath, no date) and design for disassembly and reuse or remanufacture, including the investigation and development of processes such as 'triggered degradation' (Scott, 2014) and 'active disassembly' (Chiodo, Billet and Harrison, 1999), which can potentially enable disassembly and reuse of the various elements of a smartphone, to be manufactured into new products at the end of the product's life.

Although neither the textile & clothing nor the electronic consumer goods sectors have yet fully developed viable mainstream solutions for the end-of-life problems associated with all of their respective products, and the electronic consumer industry is often accused of designing products with built-in obsolescence, while the textile & clothing industry is known to encourage cheap, 'throw-away' fashion, both industries are demonstrating serious levels of commitment to the innovation of new materials, products, processes, systems and services in order address end-of-life issues. With a particular focus on textile-based Wearable Technology, the challenges and issues at the end-of-life of such products are made even worse, as electronic elements are often embedded into or attached permanently to textiles or integrated into clothing in an invisible manner (chapter 2). This makes the recycling process much more

difficult and it is crucial for anyone involved in the design and manufacture of e-textile enabled Wearable Technology to begin to take responsibility for their future products as part of the innovation process.



Fig. 3.1: Electronic waste (a), textile waste (b) and potential future e-textile waste (c)

“Embedding electronic devices into textiles results in a novel category of products...the findings suggest that widespread application of e-textiles could result in the emergence of a new waste stream.” (Köhler, 2008, p. i)

One of the first stakeholders to highlight the conceivably devastating consequences of combining electronics with textiles, thus creating a new type of hybrid product (fig. 3.1c), was Andreas Köhler, who in his Master of Science thesis (Köhler, 2008) researched and examined potential end-of-life implications of e-textiles. This investigation was based on existing issues with electronic waste such as mobile phones, which include the release of toxic substances into the environment after disposal, health hazards to recycling workers and the potential loss and subsequent depletion of scarce materials. Köhler’s thesis demonstrated that any future recycling of textile-integrated electronics will be extremely difficult, as current textile recycling facilities and systems are not equipped to deal with this kind of hybrid product. Continuing this enquiry during his PhD research at Delft University of Technology, Köhler (2013) further predicts that if e-textiles enter recycling schemes for e-waste under the WEEE Directive, they cannot be dealt with efficiently, unless regulations are changed to include e-textiles. This important factor was also highlighted by Timmins (2009), who proposed that all electronics-based smart clothing and Wearable Technology products should be considered with the WEEE Regulations in mind, as they contain a divers range of components including electronic systems,

energy supplies and interconnecting wires, which will have an extremely negative impact on the environment during landfill or incineration.

Furthermore, it is likely that e-textile enabled clothing would enter existing recycling channels for textile waste, once the user wants to dispose of the item, and Köhler (2013) believes that traditional textile recyclers are not currently equipped to collect and process electronically-enabled textiles. This means they could become fire hazards during the sorting process due to hidden, integrated batteries, they could contaminate the fibre reclamation processes when accidentally being mixed up with ordinary textile waste and they could cause a range of problems for developing countries, where they are exported to for reuse (*ibid.*). Another obstacle for the successful recycling of electronic waste textiles is the manner that electronic and other enabling components are integrated into the textile (Timmins, 2009; Köhler, 2013; Ossevoort, 2013), as seamless integration appears to have become the ultimate aim for many textile-based Wearable Technology developments in recent years (chapter 2). In order to be able to recycle these types of products at end-of-life, designers must consider alternative and less permanent forms of integration, so they can be easily removed from clothing in order to be reused or recycled. Designers have a vital role to play in the quest to innovate new design for end-of-life strategies and both Timmins (2009) and Köhler (2013) believe that this approach should involve the planning of end-of-life issues into the early stages of the design of e-textile based Wearable Technology products.

Köhler (2013) stated that his research was stimulated by his participation in the Future Textile Expert Summit held at the Knowledge Centre for Smart Textiles at VIA University College in Denmark, where forty-five international experts from fields including electronics, textile construction, surface treatments, nanotechnology and sustainable textiles across industry, academia and research institutes came together in May 2011, to explore the future of smart textiles (Hansen Degn, Hansen and Jensen, 2011). In particular these participants identified a growing focus on environmental impacts and energy and resource saving, while recycling was identified as a mega-trend influencing the innovation process of e-textiles. One of the key conclusions of the summit was the significance of commitment to sustainability, such as the innovation of new organic and recyclable materials and development of opportunities for reuse and upcycling (*ibid.*). Regrettably, four years after the event, the summit's outcomes do not reflect the current status of the textile-based Wearable Technology industry and apart from the academic research

activities outlined in this section, there is little evidence that this industry is ready to embrace the challenges and innovation opportunities for end-of-life issues as part of their research and developments.

One could argue that this concerning lack of planning for end-of-life issues prevails because Wearable Technology is not yet considered a commodity product, although numerous market reports and forecasts indicate that the market for Smart Textiles and Wearable Technology will grow significantly over the next decade (Harrop, Das and Chansin, 2014; Juniper Research 2014; Dalsgaard and Sterrett, 2014). Indeed, in 2008, the UK Parliamentary Office of Science and Technology stated in their newsletter that *'Recycling is not an issue that most researchers are addressing. They believe smart materials are either too early in their development or used in such small quantities that this is not yet an issue.'* (Parliamentary Office of Science & Technology, 2008). However, should the Wearable Technology market continue to grow as predicted, it is imperative that all stakeholders involved in the design, development, manufacture and consequent end-of-life management of devices, clothes and accessories, look at any potential negative environmental impact associated with the design, manufacture, use and disposal of these products, well in advance of such products becoming ubiquitous commodities.

To date there has been little practice-based design research into the potential environmental impact of textile-based Wearable Technology and Köhler, who is from an engineering and science background, remains the key contributor to the discussion around end-of-life issues for such products. However, while Köhler initiated the debate by identifying and communicating potential issues with e-textile waste and started to develop and test ideas for design education through several workshops ^{3E, 3F} and the collaborative development of a lifecycle assessment tool ^{3G}, this research aims to continue and develop the conversation by presenting conceptual artefact collections, which are designed from a textile, clothing and accessory designer's perspective and demonstrate design-led solutions to inspire debate and additional interdisciplinary and collaborative work in the future.

3.3 Designing non-integrated wearable sensors

Initial research identified three types of textile-based wearable sensors (chapter 2). However, of particular interest for this project is the category of *non-integrated*

wearable sensors, which include body-worn, skin-worn and clothing-attached, removable and reusable sensors. The exploration of the design of non-integrated wearable sensors is driven by the desire to look beyond the realm of permanent sensor-integration into clothing, based on my criticism that most research projects in the fashion and lifestyle realm continue to strive for seamless sensor integration. This view is also reflected by other researchers; Timmins (2009) pointed out the critical choices that need to be made at the design stage in regard to electronic integration, as these can positively affect the potential reuse, recycling and safe disposal of a product at the end of its life, while Köhler (2013) calls for designers and developers to scrutinise and question the concept of seamless integration, especially when designing short-lived products, in order to anticipate and eliminate the issues caused by seamless technology integration at the product's end-of-life.

Although the notion of seamless integration might be suitable for specific specialist applications, such as heart rate monitoring embedded in sports bras and t-shirts, or impact monitors in helmets for contact sports, it confines the wearer to specific, often expensive items of clothing or accessories, in order to benefit from the sensor. In particular view to designing wearable sensors for Preventative Health, affordability should be a key factor, as the opportunity to take active control of one's health to prevent future of illness and diseases, should not be limited to affluent users who can afford expensive gadgets or clothing but needs to be accessible to the broadest section of the population possible, in order to have substantial impact on reducing the global healthcare burden. Indeed, research and development of non-integrated, portable or wearable, low-cost sensing for diagnostic purposes specifically aimed at users in the developing world is currently a key area of interest, as non-profit organisations, such as Diagnostics for All ^{3H} and start-up companies, such as fuseproject, are creating low-cost, easy-to-use, point-of-care diagnostic devices, including fuseproject's kernel of life ^{3I}.

Furthermore, seamlessly integrated sensors in clothing and accessories are not always practical as part of an outfit or activity, as users may wish to wear a sensor-enabled sports garment several times a day, which could cause wash care issues and such specific garments may not be appropriate to be worn in a different context, should the user wish to monitor themselves outside the activity the wearable sensor was designed for. The permanently integrated approach could cause further difficulties when the wearer wants to monitor a broader selection of parameters simultaneously, thus having to wear a collection of different garments and devices,

as most of the current wearable sensing products are limited to detecting and monitoring only a narrow range of data. In particular view to utilising wearable sensors as part of a preventative lifestyle, it is important for the user to gain a more holistic view of their health, which may involve a multitude of sensors.

In the future there may be many different types of wearable sensors available to the user to detect, collect and combine a plethora of biochemical, physiological and environmental data and should they wish to, the user could potentially cover every inch of their bodies with a growing number of wearable sensing devices. Although this extreme use is unlikely, as the availability and personal use of sensors become more ubiquitous, users may want to combine a number of different types of sensors in line with their individual lifestyles, medical history, interests and circumstances, in order to create an accurate and complete overview of their health on which they can act upon. Non-integrated wearable sensors could make it easier to allow for a personalised combination of sensors, which could be worn under, on top of or alongside existing clothing, footwear and accessories, so that they easily integrate into the users' existing outfits, activities and lifestyles. This research therefore aims to build on the emerging research and development into new types of skin-worn electronic tattoos, patches and plasters, as well as ideas for non-permanently attachable sensor devices (chapter 2).



Fig. 3.2 Misfit Shine wristband worn on leg



Fig. 3.3 Mishit t-shirt with sensor pocket

Chapter 2 highlighted issues with existing wearable sensing devices in regard to wear position restrictions imposed by manufacturers and described how some users have been experimenting with alternative on-body positions. The designers of the Misfit Shine activity tracker (fig. 2.53) considered the need for variety on wear positions as part of their development, as the device could be worn attached to

clothing, in pockets in a provided rubber wristband or as a necklace. Despite these options, some users were not satisfied with the choice of positions, while one particular user blogged about wearing the wristband around the ankle to receive accurate feedback during cycling (fig. 3.2).

The trend to customise clothing, footwear or accessories in order to facilitate sensor attachment in desired positions has not gone unnoticed and based on consumer feedback, in April 2013, Misfit filed for a trademark to add their own clothing and accessories, which could integrate their Shine activity tracker more easily. These items are described as '*Clothing, namely, outer jackets, shirts, pants, footwear, shoe soles, headwear and undergarments, all the foregoing having health monitoring sensors embedded*' (Dolan, 2013). However, rather than permanently embedding the sensors, the t-shirts and socks launched in 2014 are designed with hidden pockets, so the Shine can be worn in essential positions safely and securely (fig. 3.3). There is currently no information on whether this approach has been successful with users, however Misfit are also pursuing other avenues of how to wear their activity tracker, as they have launched a Swarovski Shine collection, which includes pendants and bracelets and solar-powered versions and is expected to ship in August 2015 ^{3J}.

3.4 Designing for a real user need

Unlike specialist applications such as healthcare & medical and military, space & industrial developments, which are generally driven by specific needs, missed opportunities for designing with real user needs in mind are a particular issue for commercial consumer applications, a segment of Wearable Technology that is often criticised for cashing in on fleeting trends and producing short-lived gadgets. Design educators at Brunel University, Ariyatun *et al.* (2005), believe that the lack of commercial mass-market success of many a Wearable Technology product are to blame on the failure of design and development teams to recognise and consider consumers' needs and following my own extensive review of commercial products and developments, I am of the same opinion. As this research is situated in a collaborative space between academic research and industry, it is therefore an integral part of the project to explore any potential user needs through '*meaningful end-user research*' (McCann, 2009, p. 45), as part of the design process.

It can be tempting for designers to apply emerging or existing technologies into new applications and in the case of electronic textile technologies, Berzowska (2004) queries some designers' motivation behind the desire to utilise electronic fabrics, urging them to think carefully about why and how they want to employ these technologies. In regard to designing concepts for wearable sensors, the potential for appealing opportunities within the field of Preventative Health and the utilisation of new types of material substrates and printed sensing technologies have been documented and discussed in chapter 2. However, the in-depth exploration of a 'real user need' within this context remains a critical element of the research process and design practice. Although biochemical and environmental sensing with a particular focus on VOCs and EMR has been identified as a potential mechanism for providing the user with an early warning system in order to protect their health and wellbeing, this research further aims to establish the complex aspects of what a user need for such an early warning system could constitute.



Fig. 3.4 'The Shirtulator' (a), 'Fabrications' concept wrist phone (b), iPod control integrated school blazer (c)

"We do amazing things with technology, and we are filling the world with amazing systems and devices but we find it hard to explain what this new stuff is for, or what value it adds to our lives...when it comes to innovation, we are looking down the wrong end of the telescope: away from people, toward technology..." (Thackara, 2001, p. 48)

Thackara (2001, p. 48) describes this balancing act between the temptation of using emerging technologies and considering user needs as '*a dilemma in innovation*', stating that while we are able to use a rapidly growing number of new technologies

to create numerous systems and products, we also need to keep a focus on what these new products are actually for and what value they could add to our lives. He strongly believes that people need to be considered *before* the technology, an approach, which speaks to the ‘technology pull’ innovation model. This model is generally understood as innovation in response to a market or user need, which has been identified through in-depth user and market research. In contrast the approach of ‘technology push’ implies that a new product is brought to market without appropriate research into potential user needs and preferences and this is often evident in the domain of Wearable Technology, where these ‘*because we can developments*’ (Dunne, 2010, p. 43), are repeatedly designed and brought to market simply because a promising new material or technology is available.

Furthermore, and as illustrated by Dunne’s conceptual ‘Shirtulator’ t-shirt (fig. 3.4 a), existing technologies and interfaces are rarely suitable for adaption into a wearable context, and in this case, the integration of a calculator into a garment contributes nothing to improve the t-shirt’s use (Dunne, 2010) or provide the wearer with an easy and appropriate way to use a calculator in situations when they might need one. In a commercial context, this is further illustrated by the case study of Eleksen’s textile-based wrist phone (fig. 3.4 b), one of a 5-piece strong concept collection featured in the ‘*Fabrications*’ book (Chapman *et al.*, 2001). Despite being presented as an iconic concept (the collection was featured in an exhibition at the Museum of Modern Art in New York and is part of their permanent collection archives ^{3K}), the commercial products developed from the concept collection never achieved the success the inventors had envisaged. Upon study of the book and literature around the design and development process, it appears that the designers were so passionate about the commercialisation of their touch-responsive material technology, that the technology became the driving force for the innovation process, which neglected to integrate a thorough investigation into potential user-needs and failed to consider possible changes in communication technologies.

Another example is Marks & Spencer’s iPod school blazer, which was launched as part of the 2008 ‘Back to School’ collection and integrated Fibretronic’s five function textile keypad controller inside the lining (fig. 3.4 c), in order to operate the iPod kept in the blazer’s pocket. This type of technology had previously been used in a collection of business suits (chapter 2), however, a technology that may have been appropriate for adult use, caused serious concern in its application for school children and was severely criticised by teachers and parents alike. It was claimed

that the jacket could lead to distractions in the classroom as well as potential technology misuse encouraging anti-social behaviour and breaking school regulations (Alleyne, 2008) and was therefore dropped from the range soon after its launch.

With a particular view to designing concepts for wearable sensors, it can be noted that there has been an astonishing influx of fitness and activity trackers since 2009, and while the segment is predicted to grow even further to over 45 million units by 2017 (Canalys, 2014), it has been reported that in the US, one-third of activity tracker users stopped using their device within the first six months of receiving it, and more than half of the consumers who have owned one, stopped using it altogether (Ledger, 2014). Indeed, the Wearable Technology industry could be accused of flooding an already saturated market, while ignoring the consumer who could most benefit from these types of sensing and tracking technologies, including elderly, chronically ill and underprivileged consumers (Herz, 2014). It is therefore imperative that any biochemical and environmental wearable sensing concepts are designed based on the outcomes of in-depth probing of user preferences, lifestyles and habits, in order to produce meaningful and relevant concepts for life-enhancing future products.

This important task can be supported by existing user-centred design approaches, which involve direct connection with potential users to identify their needs, in order to gain a better understanding of the user in context to be able to design and develop more suitable and effective consumer products and services. There are several examples of the call for and application of user-centred design methods in the context of Wearable Technology (Ariyatum *et al.*, 2005; McCann, 2009; Dunne, 2010) and with a particular focus on the design of body-worn sensors, medical researchers at Imperial College London, Bergmann and McGregor (2011), highlighted the urgent need to investigate both patient's and clinician's needs and preferences, in order to encourage user acceptance and effective adoption of wearable biomedical sensing systems. The researchers' systematic review (*ibid.*) of studies evaluating user (patient and clinician) preferences of body-worn sensors included peer reviewed journals and conference proceedings. This review revealed that only 11 studies have explored the subject to date and that the data quality was relatively low, due to limited methodologies, small subject numbers and confined reporting of the processes, demonstrating that the design of on-body sensing systems is somewhat devoid of evidence based information (*ibid.*). They concluded

that trends and user preferences need to be integrated into the early stage of the design process and my own research methodology is designed to accomplish this by embedding a thorough practice-based user need investigation into the initial and defining stage of the research (chapter 8).

3.5 Summary and conclusion

This chapter presented the neglected areas of research and emerging design opportunities in the field of wearable sensors, which constitute the following:

- Design innovation in the field of Preventative Health, with a particular look at designing wearable sensors that can act as an early warning, detection and monitoring system based on biochemical and environmental sensing;
- Design-driven exploration of end-of-life considered approaches to wearable sensor design;
- Design investigation of non-integrated types of wearable sensors as an alternative to permanently and seamlessly integrated sensing in clothing;
- Integration of a practice-based thorough investigation of user-needs into the design process, in order to inspire more diverse wearable sensor concepts.

This practice-based research is therefore concerned with contributing to new knowledge in the area of designing non-integrated wearable sensor concepts for the rapidly growing field of Preventative Health, while exploring the natural embedding of design strategies to create concepts that provide considered solutions for the product's end-of-life. Furthermore, the research endeavours to thoroughly probe diverse aesthetic and functional aspects of the design and use of a user-friendly early warning system based on biochemical and environmental wearable sensors, thus ensuring a real user need is addressed.

Moreover, although these identified gaps in knowledge represent design opportunities in their own right, they are also closely linked and the key approach of this project was to develop (chapter 4) and apply (chapters 6, 7, 8 and 9) a research

methodology, that can enable these interconnected opportunities to be explored during the *early stages* of the design process (Walker, 2006, Bhamra and Lofthouse, 2007; Sherwin, 2012; Bergmann, Chandaria and McGregor, 2012 and Köhler 2013), in order to inform the design of inspiring conceptual artefacts during the final stage of practice, so that they can contribute to knowledge in the field of wearable sensor design in the future (chapter 10).

Chapter 4: Research design and methodology

The overall aim of the design practice was to create an informative and inspiring collection of industry-facing conceptual artefacts (chapter 1) and the design and development of the research methodology was therefore critical to achieving this aim. This approach involved the combination of a range of methods and tools to provide the project's framework for investigation, in order to address particular gaps in knowledge and answer the corresponding research questions.

Although the range of methods and tools available to design researchers to gather, generate and analyse data and transform it into valuable information has been expanding, researchers are often encouraged to develop more relevant and authentic methods, which can contribute to the development and understanding of new types of methodologies, in line with their specific field of expertise. Independent researcher and consultant and research professor at Gray's School of Art in Aberdeen respectively, Gray and Malins (2004, p. 101) refer to this approach as '*methodological trailblazing*' and urge design researchers to be flexible and creative in the search for and development of much-needed alternative research paradigms, while academic design researchers at Royal College of Art, Seago and Dunne (1997) highlighted the need for the creation of more unique research strategies that reach beyond the use and modification of existing methodologies from other academic disciplines, in order to produce more original research outcomes in the field of art and design research.

This experimental attitude was highly significant for the intuitive development of my own research methodology, which was strongly influenced by my professional design practice, as it has been impossible to detach myself from the familiar and spontaneous way I respond to a design challenge. Based on the Royal College of Art study 'Design in general education' (Archer *et al.*, 1979), British academic, design researcher and educator Cross (1982) explored the concept of 'designerly ways of knowing', a term which is used to describe the specific forms of research utilised by the design community and this approach is strongly reflected in my choice and development of methods. Cross stated that the problem-solving methods utilised by designers can be broadly described as mainly tacit knowledge (*ibid.*), suggesting that these design-specific ways of knowing and doing are often difficult to express, as they are deeply ingrained in the designer's existing practice. This

point was further explored by influential American design thinker and educator Schön (1983), who coined the much-cited term 'knowing-in-action', which describes a form of practice where the practitioner's practical knowledge is implicit in the way they respond to a new challenge or practice problem, by tapping into a repertoire of experiences to enable understanding and action in new situations. Driven by my implicit knowledge gained through many years of professional practice, this project therefore integrates familiar tools and methods of research. However, it further combines these with additional methods from academic design research, in order to appropriately address the research questions and gaps in knowledge (fig. 4.1).

4.1 Significance of practice

It is important to emphasise the pivotal role practice plays in this research project and examine the relationship between research and practice. For the UK's Research Excellence Framework 2014 ^{4A}, research has been defined as '*a process of investigation leading to new insights produce new insights, effectively shared*' (The University of Aberdeen, 2014), while research is generally understood to constitute a '*systematic investigation into and study of materials and sources in order to establish facts and reach new conclusions*' (Oxford English Dictionary¹). With a particular view to design research, British educationalist and writer Frayling (1993, p. 1) states that '*Where artists, craftspeople and designers are concerned, the word 'research'...sometimes seems to describe an activity which is a long way away from their respective practices*' and with the intention to define the role and use of research in the context of art and design, introduced three different categories of research. These include research *into* art and design, research *through* art and design and research *for* art and design (Frayling, 1993). In relation to my project, research *through* art and design, which Frayling describes as utilising elements including materials research, development work and action research, has been employed in line with my professional design practice, while research *for* art and design is also an important element, as the end product is an artefact which embodies the designer's thinking (*ibid.*). The concept of embodied thinking and embedding of research findings within the artefacts is very much reflected in the approach to the final artefact collections (chapter 10), and further demonstrated in the creation of the design brief (chapter 9), which integrates selected and relevant research findings to date.

Design research is often characterised by the creation and evaluation of artefacts (Seago and Dunne, 1997, Scrivener, 2000; Biggs, 2004, Candy and Edmonds, 2010), which are utilised to drive the design enquiry and the use of artefacts was indeed a key element of the design practice in this research. The word artefact derives from the Latin words *arte*, meaning ‘by or using art’ and *factum*, meaning ‘something made’ and artefacts are further defined as ‘*an object made by a human being, typically one of cultural or historic interest...*’ or ‘*something observed in a scientific investigation or experiment that is not naturally present but occurs as a result of the preparative or investigative procedure...*’ (Oxford English Dictionary²). Different research disciplines can have diverse understandings of what artefacts may represent and even design artefacts can vary greatly in terms of the making process, format, use and outcome.

The role of creative artefacts is already well explored, although our understanding of how these artefacts can be produced, used and evaluated continues to evolve, as more practice-driven research is undertaken and disseminated. In particular view to design research, Seago and Dunne (1997) talk about the creation of artefacts, which embody the research and are capable of communicating specific ideas and concepts. British academic art and design researcher and educator Scrivener (2000) lists ‘embodied knowledge’ as one of the key features of artefacts utilised in art and design research and suggests that this knowledge should be applicable to other contexts, so that others, based on knowledge embodied in the original artefact, can construct new artefacts.

Moreover, British academic researcher Biggs (2004) refers to two interpretations of the role of artefacts; they can either communicate the research or their creation could be considered research in itself. Biggs’ interpretation highlights that artefacts can be employed in different ways and therefore the manner in which they are used can also contribute to the understanding of whether a research project is considered practice-based or practice-led, or indeed, a combination of the two. Although many design practitioners use the terms practice-based and practice-led interchangeably, they should not be regarded to be the same, as art and design practice including artefacts can be used to produce different types of findings. British academic and design researcher Wooley (2000) proposes to differentiate between the two types based on the nature of art and design practice; if practice is used to explore research questions it is practice-based, if it is used to investigate the use of methods, often from other disciplines and in order to generate knowledge that can enhance

design practice itself, it is considered practice-led. Similarly, writer and academic researcher Candy (2006) suggest that both types of design research share the same central practice element, although they differentiate in their outcomes; while practice-based research utilises creative artefacts as the basis of contribution to knowledge, practice-led research contributes to new understandings *about* practice.

Building on the above interpretations and my own research aims and objectives, this research project therefore displays elements of both approaches. The overall aim of the research was the design and development of a wearable sensor collection, in line with my desire to contribute to future concept and product innovation and the project can therefore be described as practice-based. However, as the project evolved, it became clear that in addition to the creation of various types of artefacts, which explore the research questions and therefore contribute to the outcomes in response to those questions, the creation and evaluation of artefacts also advance the understanding of effective methods and tools, thus providing new knowledge on practice itself.

4.2 Research process

The intuitive and reflective, yet systematic research process formed the framework for the exploration of a design research investigation, which was carried out in well-defined stages. This process is aligned with key elements of the Design Council's Double Diamond model, which was conceived as a way of mapping the design process in 2005 ^{4B}. The first three stages of this model, *discover*, *define* and *develop* are particularly relevant to illustrate my own instinctively planned research journey, as they concern the research, creation and development of ideas, while the final stage, *deliver*, was not relevant, as it involves the production and launch of a product or service to the consumer.

This 3.5-year research project can be clearly divided into three stages (fig. 4.1), which comprise *discovery* of the gaps in knowledge and design opportunities for wearable sensors, *definition* of the research questions and particular design practice focus and the *development* of the final conceptual proposals and although I was not aware of this model prior to this research, these stages resonate naturally with my professional design practice and tacit knowledge of the design process. The diagram is structured in a linear manner, however, certain elements of the research,

such as the contextual and literature review, were developed and revisited at various stages throughout the research, as the field continued to evolve. In addition, final clarity on the identification of design opportunities and gaps in knowledge, although originally identified following the initial contextual & literature review in year one, continued to crystallise during the design practice in the definition phase and was therefore revisited and finalised prior to the formulation of the design brief. This process is referred to as 'reflection-in-action' (Schön, 1983) and describes an approach where the process of practice (data generation) and reflection (data evaluation) are natural elements of the research and design process. 'Reflection-in-action' was a continuous element throughout this research project and was utilised to drive 'next steps' of research and practice, before culminating in a final evaluation following the completion of all design work.

Elements of this reflective research process are further aligned with American educational theorist Kolb's (1984) 'experiential learning cycle' model, which is based on the understanding that '*Learning is the process whereby knowledge is created through the transformation of experience*' (Kolb, 1984, p. 38) and is defined by four stages. These include 'Concrete Experience', 'Reflective Observation', 'Abstract Conceptualisation' and 'Active Experimentation' and comprise activities such as doing, i.e. having an experience, consciously reflecting back on that experience, conceptualising a theory based on learning from the experience and testing out a model or concept of what has been learned (*ibid.*).

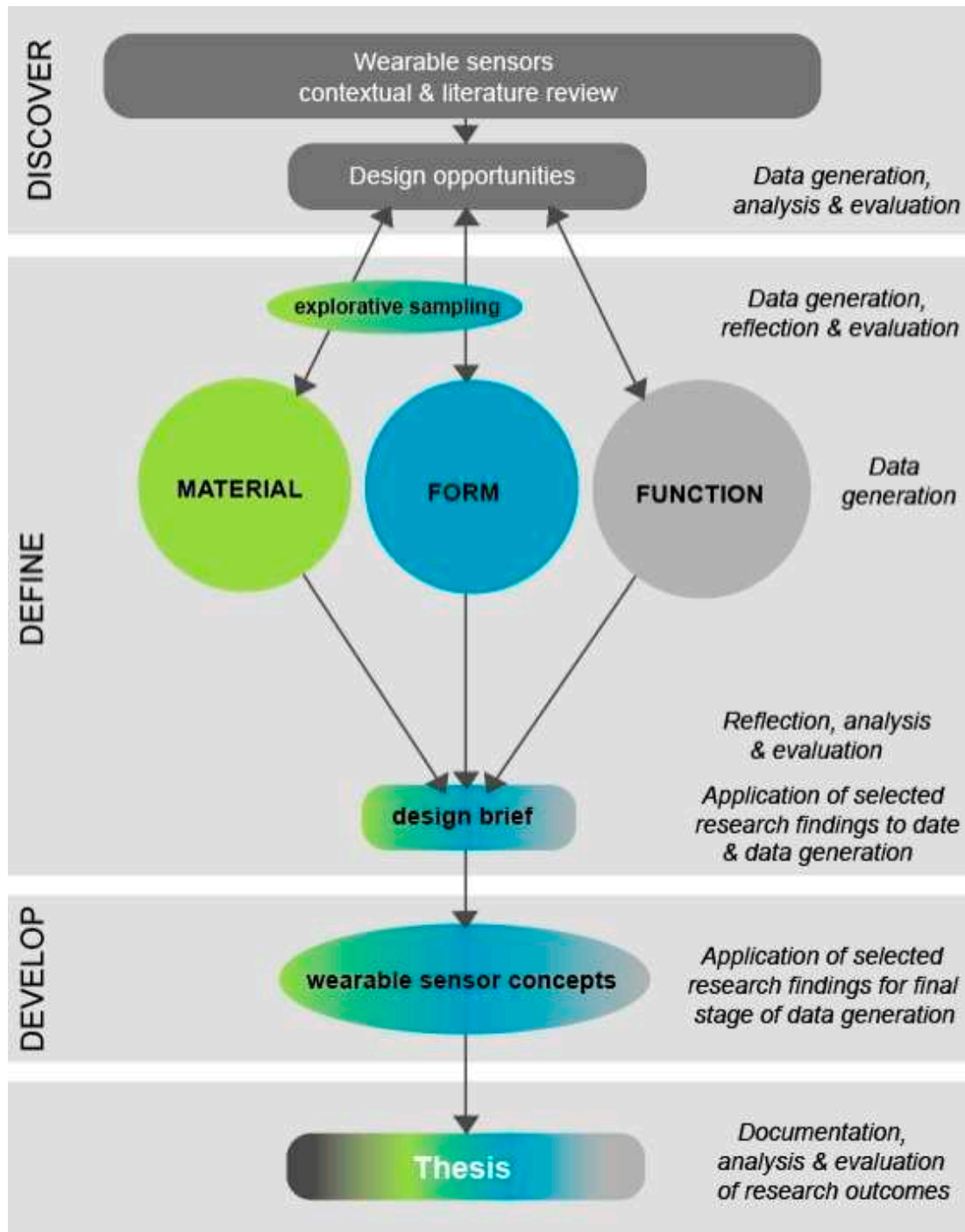


Fig. 4.1: Research map, Prahl (2014), based on the first three stages of the Double Diamond model (Design Council, 2005)

The *discovery phase* was concerned with the investigation of existing and emerging academic and commercial research, developments and products in the realm of textile-based Wearable Technology, with a particular look at wearable sensors, in order to understand and evaluate the territory and context in which the research is situated (chapter 2), while providing a solid knowledge base for the identification of gaps in knowledge and emerging design opportunities (chapter 3).

The *definition phase* was critical to the successful development of the project and proved to be the most intensive stage of the research. This journey of exploration first saw a spontaneous and unscripted phase of explorative sampling, which was inspired by developing samples for an event at the Smart Fabrics San Francisco Conference in 2013 ^{4C} (chapter 5). This activity and subsequent evaluation inspired the focus on three strands of investigation (section 4.2.1), which produced an abundance of relevant data (chapters 6, 7 and 8), evaluated to inform the design brief (chapter 9). Finally, the *development phase* involved the design of five wearable sensor collections, which comprised the creation of mood and inspiration boards, material boards, design sheets and samples (chapter 10). The completion of the collections marked the end of the design practice and was followed by the evaluation of the research project's outcomes, as part of the writing-up of the thesis.

4.2.1 Three-stranded enquiry

Based on the identification of gaps in knowledge and design opportunities (chapter 3) and the initial phase of explorative sampling (chapter 5), it became apparent that the research project would benefit from focusing on specific aspects, in order to address these design opportunities accordingly. It was therefore central to the research to devise a three-stranded investigation, which could conceptualise these particular fields of interest, while creating boundaries and limiting the investigation to a feasible breadth. Furthermore the division of the research into three individual but firmly linked strands enabled the integration of the key enquiries into the early stages of the design process (chapter 3) to allow the identification of initial and broader research statements (fig. 4.2), which evolved through more specific research questions (chapters 6, 7 and 8) to the overall design proposal (chapter 10), as the design research process progressed.

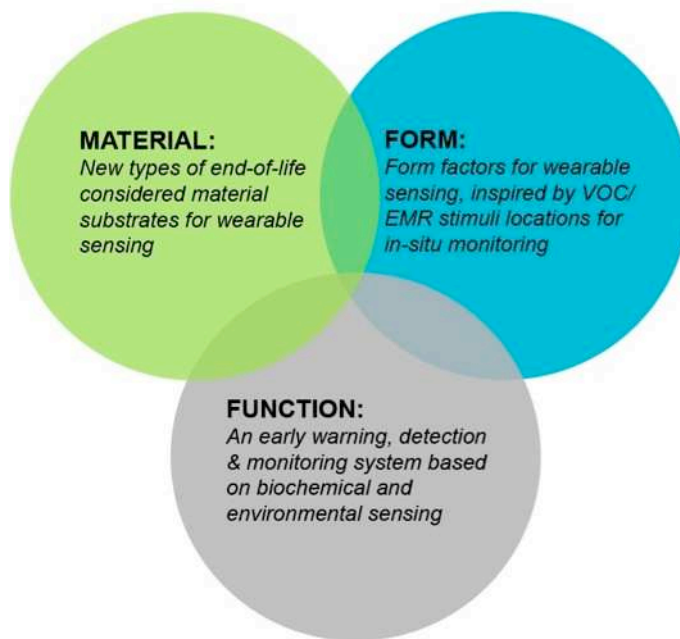


Fig. 4.2: 'Three strands of enquiry', Prahl (2014)

In summary, the overall aim of the three-stranded investigation was to:

- Explore new types of wearable end-of-life considered material substrates for wearable sensing ('MATERIAL');
- Develop new form factors for wearable sensors inspired by VOC/ EMR stimuli locations for in-situ monitoring ('FORM');
- Investigate the use-case for an early warning, detection and monitoring system, based on biochemical and environmental sensing ('FUNCTION').

In addition, the focus on material, form and function directed the methods of enquiry, as they naturally correspond with the type of data I set out to gather and generate in order to address the initial research questions. This approach has been discussed by American sociologist, author and co-creator of grounded theory Strauss and researcher and co-author Corbin, who, in their book 'Basics of Qualitative Research' (Strauss and Corbin, 2004, p. 39-40), state that specific issues should clearly propose the most suitable types of research. This project demonstrates the important relationship between the research questions and the methods used to address them, highlighting the design researcher's opportunities for the creation, adaption and adoption of authentic and appropriate methods to successfully explore their questions.

4.2.2 Data collection, generation and evaluation

Within the context of design research, the meaning of data can be baffling to any designer new to academic research. Data is generally understood to mean '*facts and statistics collected together for reference or analysis*' (Oxford English Dictionary³), which appears to leave little scope for creative interpretation. However, Newcastle University's definition of data, '*...anything that has been produced or created during research*' (Newcastle University, no date), is a more flexible guide for design researchers, as it is widely understood that data can include documents (such as spread sheets and charts), field notebooks and diaries, diagrams, questionnaires, audio and video recordings, photographs, films, blogs, artworks, designed artefacts, samples and sketchbooks.

Research data can further be categorised into *quantitative* and *qualitative* data and social research expert, academic and author Punch describes qualitative research as empirical research '*where the data is not in form of numbers*' (2014, p. 3), while Strauss and Corbin (1998, p. 10-11) characterise qualitative research as '*... research about persons' lives, experiences, behaviours, emotions and feelings, as well as about organizational functioning, social movements, cultural phenomena and interactions between nations*' and deem the collection and generation of qualitative data as the most productive approach to provide an '*effective method of discovery*' (Strauss and Corbin, 1998, p. 1). In order to address the research questions and inspire the design of the final artefact collections, this project therefore focused on the collection, generation and evaluation of qualitative data.

Design inspiration plays an important role in the design process and can be achieved through many different techniques, depending on the nature of the design problem or brief. In my professional practice, suitable mechanisms for inspiration, generally carried out at the beginning of the creative process, have involved a multitude of activities. These include primary and secondary market and product research, travel to specifically selected locations, participation in specific activities relevant to the products I was designing, magazines, cultural events and exhibitions and the use of trend forecasting books and websites. In an academic design research context, the collection and generation of primary data; data that is generated by researchers themselves and for the specific purpose of their study, through participation in activities such as observation, action research, case studies, questionnaires, ethnographic research and interviews, or data generated by practice,

is particularly significant. In contrast, secondary data describes data that already exists and has been generated, or previously identified by others and is often relatively easy to obtain. This type of data includes existing research (i.e. papers and reports), mass media products, government reports, Web information, official statistics and historical data and information. In combination, both types of data played important roles; while secondary data provided the framework for the context and scope of the project, the generation and evaluation of primary data acted as the creative driver behind the design practice.

This symbiotic relationship between data generation and practice, analysis and evaluation was an important part of my design process (fig. 4.1) and is associated with grounded theory, which Strauss and Corbin (1998, p. 12) described as '*...theory that was derived from data, systematically gathered and analysed through the research process*'. Strauss and Corbin (*ibid.*) further refer to American author Sandelowski (1995), who remarked that although the grounding of concepts in data is a significant feature of this method, the researcher's creativity also plays a significant role. They further elaborate that this involves their ability to pose thought-provoking questions, make relevant comparisons, identify categories and develop appropriate concepts from their generated and gathered raw data (Strauss and Corbin, 1998, p. 13).

Design researchers need to evaluate their collected and generated data as it serves as the evidence for their research argument (Gray and Malins, 2004). In order to make the research outcomes relevant, valuable and meaningful in a broader context, this project demonstrates the process of evaluation through the generation of artefacts, which were analysed and evaluated at various stages of the research (section 4.2, fig. 4.1) to answer research questions and inform the next stage of practice. Beyond the generation of data as the driver of my own research project, this research further aims to inspire other design researchers in the future and it is therefore important to make the research findings accessible, usable and potentially replicable by others. Relevant research data is therefore available as a combination of text, diagrams and images in the main body of the thesis, the form of appendices and on a digital storage device (appendix D).

4.3 Research methods and tools

The combination of different types of methods, both adopted from my professional design practice and more unfamiliar methods adapted from academic and industrial design research (fig. 4.3), was a practical tool for the generation and evaluation of the diverse data utilised to inform and inspire the design and development of the wearable sensor collections.

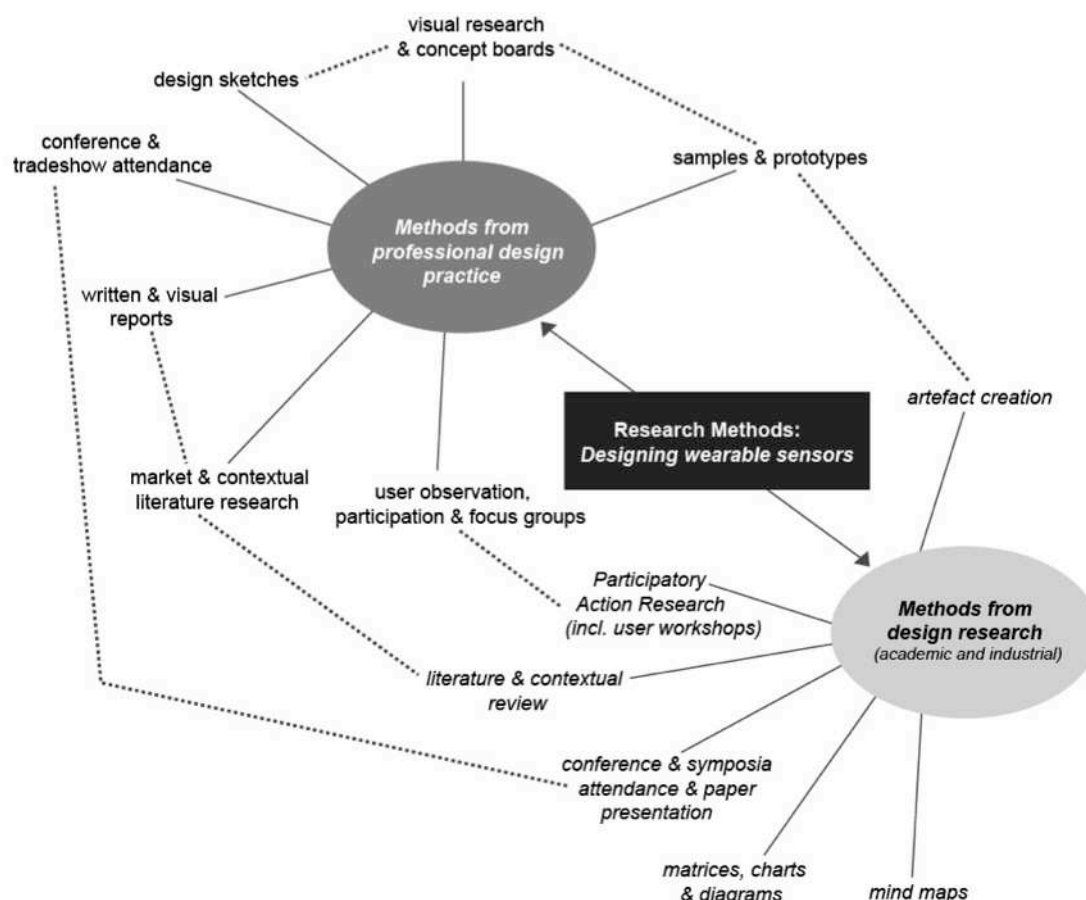


Fig. 4.3: Research methods & tools, Prahla (2015) based on Gray & Malins (2004)

I was already familiar with various methods and tools (fig. 4.3), which included: market/ contextual literature research, conferences/ tradeshows, written and visual reports, user observation and participation in specific activities related to the end-product, focus groups, visual research/ concept boards, design sketches and samples and prototypes. Although there are advantages in relying on existing experiences to tackle a new design challenge, Schön (1983) also identified potential limitations of this intuitive and spontaneous approach, as it may not encourage sufficient in-depth reflection. In regard to my own project it was therefore important

to examine and develop unfamiliar methods in addition to the tools I was accustomed to using in my professional practice. These methods from the field of academic and industrial design research (fig. 4.3) included a literature and contextual review, mind maps, matrices, charts and diagrams, Participatory Action Research including user workshops, conference and symposia attendance, writing and presentation of conference papers and the creation and evaluation of artefacts. As indicated by the dotted lines, most of the methods utilised were inspired and adapted both from professional practice and academic and industrial design research, in order to provide suitable tools for this project.

While my experience with relevant methods from my professional design practice contributed to confident and intuitive choices of methods, this approach could have caused disadvantages as the lines between methods from professional practice and academic design research were blurred in some instances (fig. 4.3), thus potentially affecting the objectivity, reliability and validity of the generated data and the quality of the research. However, this research employed the multi-method of combining two or more different methods and this approach is referred to as triangulation. Academic researchers and authors Lewis-Beck, Bryman and Liao (2004, p. 1142) define triangulation as '*...the use of more than one approach to the investigation of a research question in order to enhance confidence in the ensuing findings*' and this method enabled me to ensure that my qualitative data is more valid and dependable, thus making the design research stronger and more relevant for other researchers.

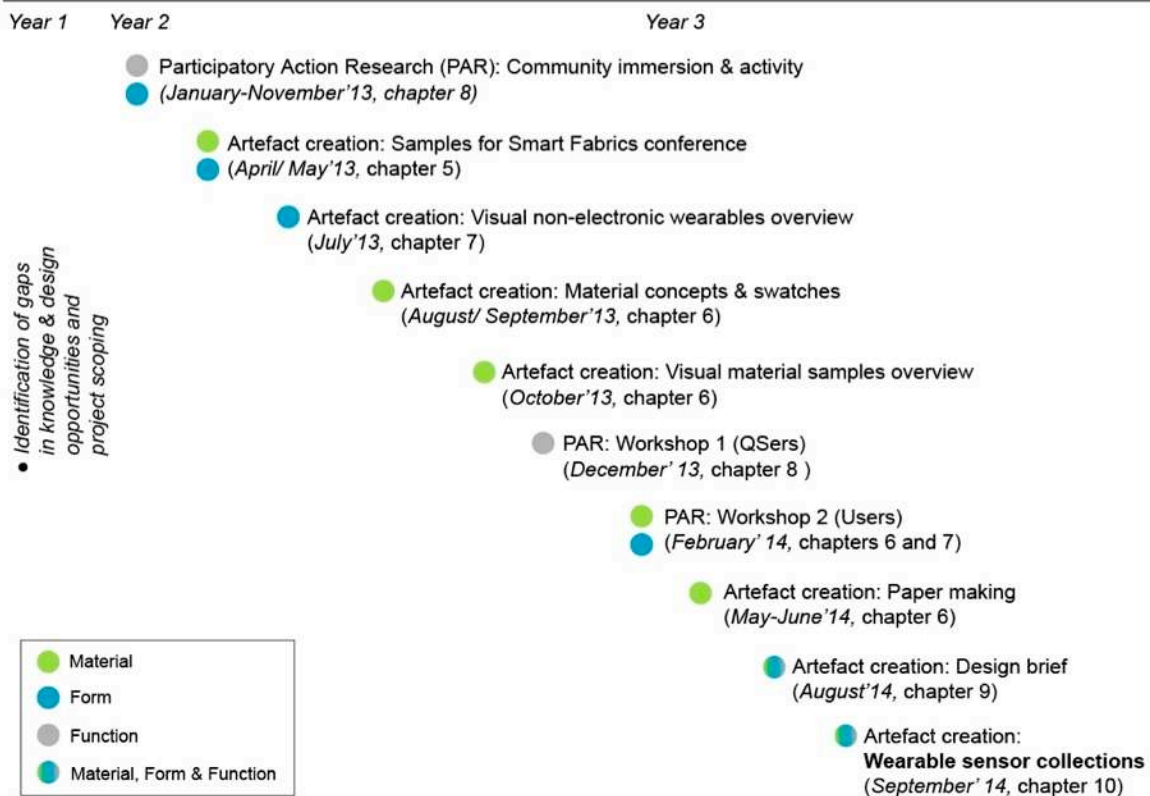


Fig. 4.4 Key practice-based methods timeline, Prahl (2015)

In line with the pivotal role of practice within this research, a strong emphasis was placed on the use and adaption of *practice-based* methods to generate suitable data to inform and inspire the design of the final artefact collections and the timeline (fig. 4.4) gives an overview of these key methods in the context of the development of the research, while they are explained in more depth in sections 4.3.1 and 4.3.2.

4.3.1 Key practice-based methods: Participatory Action Research (PAR)

In order to genuinely explore gaps in knowledge, it was important to experience certain aspects of wearable sensing as a *user* and immerse myself into the field, both through participation and engagement with a variety of potential users. Furthermore, the key aim for the utilisation of various methods associated with PAR was to generate primary data that could contribute to the understanding of the issues and opportunities (chapter 3), while stimulating new design ideas for the wearable sensor concepts to be produced during the final stage of practice.

The general framework for the investigation of the 'Function' strand (fig. 4.2) was informed and inspired by the field of Design Ethnography, which was described by ethnographic researchers and authors Salvador, Bell and Anderson, (1999, p. 36) as a method that *'...focuses on the broad patterns of everyday life that are important and relevant specifically for the conception, design, and development of new products and services'*. This approach builds on the importance of generating empirical data, by actively involving the design researcher in observation, participation and reflection, in order to challenge their assumptions and pre-conceptions about potential user needs, behaviours and preferences. The intention to conduct this part of the research both *with* users and as a user *myself* was informed by my participation in the SKIP Design Ethnography workshop in 2012, which was part of a series of workshops provided through a joint AHRC grant between University of the Arts London, the Royal College of Art and Kingston University ^{4D}. These workshops aimed to equip design research students with the practical understanding of specific research methods and the experience helped me to gain insights into a variety of ethnographic methods suitable for this project.

During the workshop I was introduced to the concept of 'deep hanging out', which inspired the planning of this important element of the research. The term was first coined by American anthropologist Renato Rosaldo (Salvador, Bell and Anderson, 1999), and is used by anthropologists, ethnographers and design researchers to define the researcher's often informal immersion in a specific culture, group or experience in order to observe and study behaviour through active participation. The activity of 'deep hanging out' can be considered as an element of the broader approach of Participatory Action Research (PAR) and this people-centred approach enables the design researcher to relinquish familiar routines and forms of research and interaction, while developing their project through a deep understanding of the relevant community they have chosen to immerse themselves in.

I chose to work closely with a particular group of potential wearable sensor users, the Quantified Self community (chapter 8). Members of this community (also known as QSers) engage in gathering, managing, analysing, sharing and comparing personal data, in order to enhance health, wellbeing and quality of life, activities which are often described as self-tracking or life logging (chapters 2 and 8). The process and outcomes of the various elements utilised (user research & community immersion, self-tracking experiment and user workshop) are presented in chapter 8, while the background to these elements is outlined in this section.

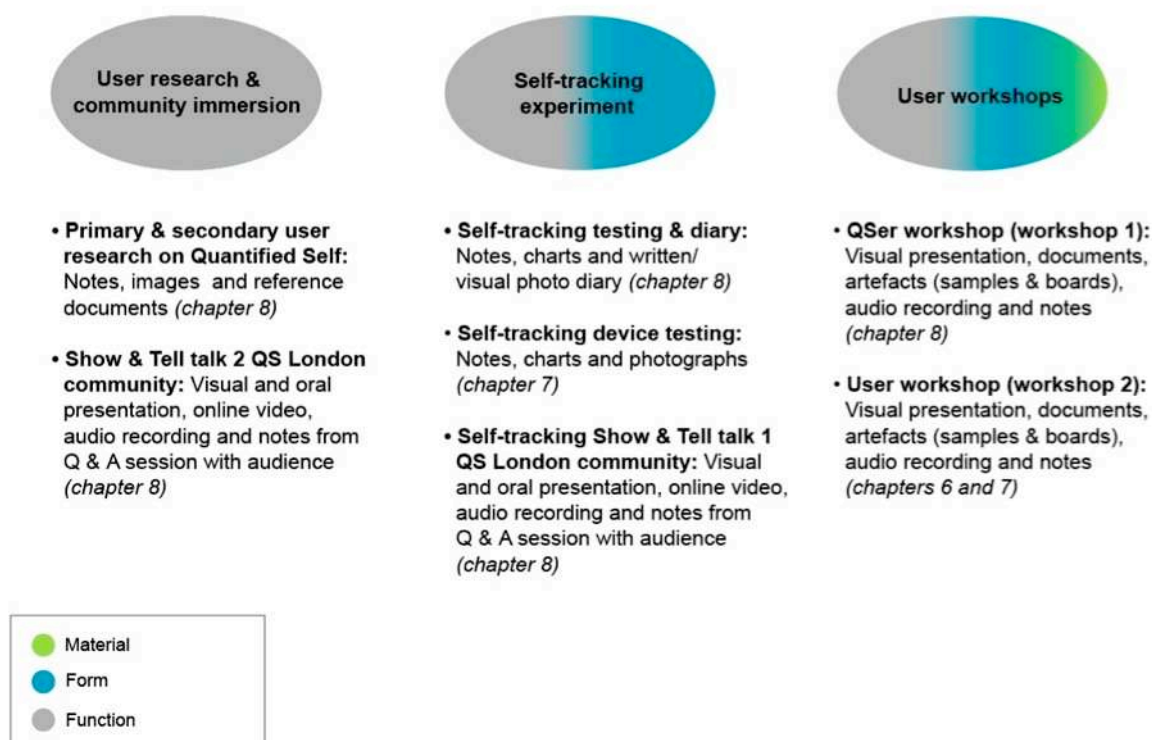


Fig. 4.5 PAR methods and data generated, Prahl (2015)

PAR methods were originally chosen to drive the 'Function' investigation (chapter 8), however, as illustrated in the diagram above (fig. 4.5), this approach further contributed diverse data to both the 'Form' (chapter 7) and 'Material' (chapter 6) investigations throughout the definition stage of the research and the produced data and outcomes of all three strands of investigation are presented in the respective chapters.

User research & community immersion

The initial phase of user research, which was a fundamental element in developing an understanding of the user in context, involved the familiarisation with the QS community and movement. This period included desk-based research such as the online study of QS conferences and the QS website, in combination with contextual literature, such as specialist blogs and online editorials. Initially there was a relatively small amount of information available, however this changed dramatically throughout the research, as the phenomenon of QS became more widespread and lead to numerous TV and Radio programmes and magazine articles. The next stage of user research involved my active immersion into the London-based Quantified Self community, which included attendance of and participation in bi-monthly 'Show

& Tell Meetups'. These meetings provided the opportunity to listen to presentations with a focus on personal self-tracking experiences, learn about the various tools and devices available and network with other members during and following the events. Participant observation is often employed in user-centred research in design, and academic design researchers at Loughborough University, Lofthouse and Lilley (2006) describe the benefits of this method, particularly in the early stages of a project, as a range of tools and techniques to facilitate the researcher's access to consumers' thoughts, beliefs and behaviours. This stage focused specifically on the investigation of user behaviours and preferences, including what data to generate and why, how to manage, display and utilise it, what the key existing devices used for self-tracking are and how they are currently worn or customised.

Self-tracking experiment (active participation)

The next stage included the application of the method of 'deep hanging out', and involved an intense period of self-tracking, in order to experience and understand a variety of potential issues and opportunities around utilising, wearing and managing self-tracking devices, tools and apps (chapter 8). The idea for this self-tracking experiment was inspired by my initial community immersion, which led to the desire to understand potential future users and their particular needs within the context of designing wearable sensors. Having previously experienced user observation and participation in my professional practice (i.e. focus groups, questionnaires and participation in relevant sporting activities), it was further important to develop these familiar tools in combination with more academic approaches.

Based on the method of participant observation, I took this approach one step further by becoming a user of self-tracking tools and devices myself, thus 'observing' myself as a participant by documenting, analysing and evaluating my self-tracking experiment. This activity served a two-fold purpose; firstly the generation of data with regards to the general experience of self-tracking (rather than focusing on the actual self-tracking data, such as running performance weight-loss and happiness, itself) in order to inspire design ideas, and the opportunity to create a 'Show & Tell' presentation, based on the experience, which would be shared and discussed with the London QS community for feedback. Through the presentation and discussion of this experience, I could also show the community that I was genuinely interested and participating in Quantified Self, which was an important element of establishing trust and social intimacy (Salvador, Bell and Andersen, 1999) with the community in general and potential future workshop participants in particular. This method of

active immersion can be likened to what is described as 'fieldwork' in ethnography and in combination with participant observation and other research methods, offers great potential to generate rich and inspiring data to the design researcher. Salvador, Bell and Andersen (*ibid.*) describe this as the belief that researchers can learn by doing and by watching, and the process, outcomes and evaluation of this community immersion are presented in chapter 8.

User workshops

The final stage of PAR included the design of two different user workshops, which were conducted with two particular user groups. The concept, planning, execution and evaluation of these workshops were inspired by a combination of my experiences with focus groups carried out as part of my professional practice, as well as the understanding of focus groups as an academic qualitative research method. However, I chose the term user workshop, as it implies a less formal and more exploratory involvement for the participants. It is generally understood that focus groups are a form of qualitative research, that bring together a group of people to probe their diverse perceptions, opinions and beliefs towards a topic of mutual interest to the participants and the researcher, in order to generate data. Focus groups are highly suitable for design research, as they can complement other user-centred research activities, such as participant observation and interviews and American academics Tremblay, Heyner and Berndt (2013) believe that they are a particularly appropriate method to refine and evaluate design artefacts. They further state that this type of direct interaction with participants provides the flexibility to cover a wide range of design topics, while enabling the probing of specific issues and artefacts, in order to generate considerable amounts of qualitative and quantitative data, which would not have been discovered in interviews with individual participants (*ibid.*).

The interactive elements of the workshops were key to the generation of inspiring data and the activities/ discussions for both workshops were carefully prepared and considered, in order to provide information on pre-determined topics. Academic researcher, educator and author O'Reilly (2008) highlights group discussions as one of the key concepts in ethnography and differentiates between opportunistic and planned discussions; while she characterises opportunistic discussions as a blend of a naturally occurring discussion and a focus group, she refers to planned discussions as a more intentional and purposeful method, which, although based on methods employed in traditional focus groups, needs to reflect a less rigid and

'textbook' (*ibid.*) approach. These considerations are reflected by my own approach to the planning and development of the workshop; while I had specific and carefully considered questions in mind, I also needed to create a space to facilitate meaningful interaction and discussion, which provided participants with the freedom to spontaneously respond to each other, while making sure that the discussion stayed on the topic of interest. Tools employed during these interactive sessions are described and evaluated in chapters 6, 7 and 8.

One of the great advantages of working with the QSer group was that many of the members already knew each other and that by being active members of the QS London group, already had a potential connection with the topic I was investigating (background on this community is presented in chapter 8). However, I was aware that this advantage could also be considered a drawback in terms of the diversity of data generation and research outcome, as members of this community are generally considered to be enthusiastic about the use of technology, which would reduce the breadth of feedback and ideas to inspire the project. I therefore decided to recruit a second group of potential future users, who were unfamiliar with the activity of self-tracking. Although both workshops shared several elements in terms of planning, methods and tools (i.e. the use of an introductory presentation, artefacts, questionnaires and an interactive session/ discussion) and process, they also differentiated in terms of recruitment and process. Detailed descriptions of the workshops' process, outcomes and evaluation are presented in chapters 6 and 7 (workshop 2) and 8 (workshop 1), while the following section compares how participants were recruited and which tools were utilised as part of the workshops:

Workshop 1 (QSers):

- The recruitment process for this workshop was time-consuming, as it involved several recruitment methods including announcements and personal discussion during networking sessions following my self-tracking talks during QS London Meetups and the utilisation of the QS London Meetup online member's page which enables members to post comments and communicate with each other
- The use of this online network allowed me to target specific members, either because I had met them in person and felt they would make suitable participants or because their online profiles stood out

- I took care to invite an equal number of women and men across a broad age range, in order to encourage diverse feedback and although a larger number of women originally planned to attend the workshop, 2 women and 5 men attended on the night, ranging from the age of 26 to 45
- The workshop used a carefully designed introductory presentation to brief participants on the research project and its context before moving on to the discussion of two pre-determined questions (utilising a series of artefacts) and culminated in participants' answering a questionnaire, which focused on the QSers' understanding and potential use of digital wearable tools to improve quality of life and health & wellbeing
- In line with the selected pre-determined questions, the evaluation of the generated data (questionnaire, audio recording, photographs and handwritten notes) was conducted by identifying key themes, which were most relevant to my ongoing research and development of the design practice

Workshop 2 (Users):

- In contrast to workshop 1, recruitment for workshop 2 focused on the assembly of a less specific and more varied group of potential users, who were interested in technology, fashion & textiles or health & wellbeing
- As with workshop 1, I made sure to invite an equal number of women and men, across the same broad age range (26 to 45) and although an original number of 5 women and 6 men agreed to participate, the workshop was attended by a lower number (1 woman and 4 men) due to London Transport issues on the day
- As with workshop 1, I prepared and used an introductory presentation to brief participants on the research project and its context, before moving on to an interactive session, which involved users having to answer several pre-determined questions (utilising a series of artefacts in combination with a questionnaire) and culminated in participants' group discussion on their responses
- As with workshop 1 and in line with the selected pre-determined questions, the evaluation of the generated data (questionnaire, audio recording, photographs and handwritten notes) was conducted by identifying key

themes, which were most relevant to my ongoing research and development of the design practice

In summary, the difference between the two workshops reflects that workshop 2 was developed following workshop 1 and therefore had the advantage that I could evaluate previous methods and outcomes, before designing workshop 2. Furthermore, my original intention was to run the same workshop (addressing the same questions and utilising the same methods and materials) with two different user groups. However, as the project evolved it became clear that I had more specific question to address and these mostly concerned the investigation of material and form, rather than function, which was the focus of exploration for workshop 1. I also considered to bring together participants from the two different user groups into a third, mixed workshop, however, as the idea behind these workshop was to generate design inspiration for the final stage of practice and I had already produced a sufficient amount of data to inform and guide my next creative steps based on the two different workshops, this was no longer necessary.

4.3.2 Key practice-based methods: Artefacts

As described in the introduction of this chapter, the use of artefacts was a key feature of this project, as different types of artefacts were produced and used at various stages of the project. The generation, analysis and evaluation of *exploratory* artefacts is presented in chapters 5-9 and culminated in the design and development of a *final* collection of artefacts (chapter 10).

Final collection of artefacts (wearable sensor collections)

In line with the original main aim of the project to create a collection of artefacts and what role they were intended to play (chapter 1), Scrivener (2000) stated that the successful use of artefacts could contribute to positive change and innovation. He further explained that: a) artefacts are created as a product of the project and these artefacts can be new or improved versions of an existing product, b) artefacts can be considered a solution to a identified problem that is of interest to others and demonstrate this accordingly, c) the solutions demonstrated by these artefacts must be useful, d) the knowledge represented by the artefacts can be described and are widely transferable to the construction of other artefacts, and e) that beyond their intention as part of a specific research project, the knowledge demonstrated within

artefacts is more important than the artefacts themselves (*ibid.*). Indeed, the final artefact collections (chapter 10) demonstrate several of the characteristics listed by Scrivener and therefore contributed significantly to the research outcomes and contributions to knowledge (chapter 11).

As creative artefacts can be utilised to address a broad range of research questions and issues, there are different types that design researchers can choose to work with, subject to their chosen intention. In his book 'Design Activism: Beautiful Strangeness for a Sustainable World', design educator, writer and activist Fuad-Luke (2009) outlines four main types of design artefacts - demonstration, service, protest and propositional - all of which can take on an activist role and have a valid role to play in design research. Demonstration, service and protest artefacts were first discussed by sustainable design researcher, author and practitioner Thorpe (2008, p. 11), who described demonstration artefacts as '*demonstrating alternatives that are superior to the status quo*', service artefacts as '*humanitarian aid for a needy group or population*', and protest artefacts as '*confrontational, even offensive, prompting reflection on the morality of the status quo*' (*ibid.*). The definition of the propositional artefact is based on academic design researcher and author Stuart Walker's work ^{4E}, which involves the use of this type of artefact as a vehicle to explore design theory in practice, generally used to explore and demonstrate ideas around sustainability (Fuad-Luke. 2009).

Due to my ambition to produce a collection of inspirational and conceptual artefacts as the practice-based outcome of the project and in line with the types of artefacts described by Fuad-Luke, I therefore consider the final collection of artefacts to be a combination of propositional and demonstration artefacts. These artefacts embed specific aspects of sustainable design by investigating and developing material substrates based on closed-loop design principles, while demonstrating positive alternatives, such as the pursuit of non-integrated wearable sensors, in order to highlight opportunities for end-of-life considered, easy-to-wear devices, which could enable a preventative lifestyle as part of a preventative healthcare strategy. Furthermore it is important to point out that I used some of these artefacts (mood, concept and inspiration boards) during the final stage of design practice, in order to inspire my own subsequent design process (design sketches and samples). The format of the conceptual wearable sensor collections (artefacts including visual boards, swatches and commercially available reference samples, design sketches and samples,) was further determined by the way they are intended to be used

following the completion of the research project, which includes: a) academic dissemination (i.e. published thesis, papers and conference presentations) and b) professional industry application (i.e. conferences, editorials, trend prediction and design projects). However, the artefacts presented as part of this thesis may be further developed for future dissemination and use (chapter 11).

Exploratory artefacts

I created and evaluated exploratory artefacts throughout the earlier research stages, which, through their creation and evaluation, were intended to inform and inspire the final collection of artefacts. Candy and Edmonds (2010) suggest that design researchers and practitioners can utilise artefacts to generate research questions and investigate answers through additional making activities. This approach is reflected in the types of artefacts generated as part of the definition phase and they include visual mood, inspiration and concept boards, material swatches and material and sample overviews and samples/ prototypes, some of which were used for my own information, while others were also used as part of the user workshops (fig. 4.5 and chapters 6,7 and 8).

The use of visual research, inspiration and concept boards was inspired by the way I work in my professional practice and these types of boards are also utilised industry-wide in textile and fashion design. Research boards generally collate relevant images in order to create systematic yet visual overviews of existing products, technologies and applications, to provide a starting point and contextual framework for any new concepts and designs and examples of these types of overviews are presented in chapters 6 and 7. In a fashion design context, mood and inspiration boards are often used to tell a story or create a theme to inspire the design of a collection or a range of products. They usually bring together a selection of images (i.e. sourced from the Internet, magazine cuttings and photographs taken) as well as fabric swatches and other relevant inspiration materials, however the format can vary greatly depending on the designer and the end product.

These types of boards are essential qualitative research tools during the early stages of the design process and can help the designer to gather initial ideas and inspiration in a focused manner. Indeed, British academic researcher and educator Cassidy (2011, p. 225) values certain types of mood boards as a “...*vital part of the design process, able to facilitate creative and innovative thinking and application...*” and suggests that the creation of these boards is a combination of a coherent

process with creativity. In an industrial context, such as product and fashion design, concept boards are used as tools to formulate and visualise more developed ideas, prior to the commencement of a product's design and development and often respond to a particular design brief. Wearable Technology researcher, designer and Visiting Professor in Smart Clothes at the University of South Wales, McCann (2009, p. 77), describes design concepts as *'multimedia presentations that provide a visual explanation of design problems to be addressed'* and various types of concept boards were produced during the definition stage of the project (chapters 6 and 9).

Other important types of artefacts employed throughout the research project include textile and material swatches and samples and these formed an important part of this research, as the design and making of explorative swatches (chapters 5 and 6) were a driving factor of the project development and final outcomes. In addition to designed and made artefacts, it is important to point out that commercially available artefacts were also utilised to provide ideas for innovation opportunities for wearable sensor materials and form factors (chapter 6 and 7). In the textile & clothing industry prototypes or samples (i.e. garments, accessories and footwear) are utilised to facilitate the development of suitable and fit for purpose commercial products. The designer often works with technical and development teams to develop these samples based on design sketches and specification sheets, which instruct the specialist manufacturers about aesthetics, shape, size, fabrics, trims and other relevant components subject to the end-product. Samples/ prototypes can then be reviewed in terms of the relevant criteria, in order to be signed off, so they can be mass-produced.

Global innovation and design company IDEO's senior interaction designer and Chief Creative Officer respectively, presented a paper on 'Experience Prototyping' (Buchenau and Fulton Suri, 2000), which highlighted the significant role that prototyping plays in enabling designers and their team members in *'...understanding existing experiences and context, exploring and evaluating design ideas and communicating ideas to an audience'* (*ibid.*). They further explain the concept of 'Experience Prototyping' as *'...any kind of representation...that is designed to understand, explore or communicate what it might be like to engage with a product...we are designing'* and suggest that prototypes, as embodiments of a design, can be utilised to help designers with decision-making during the design process. This participatory and experiential approach resonates especially with the samples produced during the early stages of design practice, as they were made to

be worn in the particular context of an evening event during the Smart Fabrics conference, which involved wearing the samples, in order to *experience* wearing them and to invite questions and feedback from other attendees (chapter 5).

4.4 Summary and conclusion

The research methodology is characterised by its range of methods, which have been adopted, adapted and combined both from tried and tested methods utilised in my professional practice, as well as more unfamiliar techniques and procedures from the field of academic and industrial design research. Practice-based methods, which include both Participatory Action Research and the creation of various types of artefacts, acted as the key drivers for diverse data generation, which initially took place as part of a three-stranded investigation model, in order to provide the necessary focus and boundaries in a complex field of enquiry.

The three-stranded approach evolved in response to the identified gaps in knowledge and in line with my personal research interests. Although this provided much-needed focus in order to address the initial research questions, other potentially relevant aspects could not be pursued in any depth (chapter 10). Most of these aspects are situated outside my own range of skills and design experience and although I do not consider this as a drawback in regard to the outcomes, at times this caused dissatisfaction during the research practice. However, these limitations highlight the importance of cross-disciplinary collaboration in this complex domain of textile-based Wearable Technology and illustrate the need for research methodologies that can involve diverse teams of experts in their application.

PAR included user research and community immersion, active participation and user workshops and the data generated through these methods proved highly inspiring to the progress of the project in general and the development of the five user type concepts for the design brief (chapter 10) in particular. It is worth noting that I utilised these established user-centred research methods in order to elicit responses around initial ideas and design concepts to inspire my own design work, rather than to test any concepts or finished designs for user acceptance or usability. Exploratory artefacts including visual overviews, concept boards, swatches and the design brief, played a key role in motivating the design practice and contributed to

the satisfactory design and development of the final artefact collections, which were created to demonstrate emerging design opportunities to the Wearable Technology community in an inspiring manner. However, as there has been no opportunity to test these industry-facing artefact collections with their intended audience, I am unable to evaluate this method in terms of the artefacts' format, intention and impact, beyond their relevance for my own design practice as part of this research (chapters 10 and 11).

While the creative combination of familiar and unfamiliar methods and tools, the use of PAR, a focus on three interlinked strands of investigation and the use and creation of various types of artefacts and are not in themselves groundbreaking, the development and application of this experimental methodology demonstrated how design researchers could adapt, modify and develop existing methods in order to inspire and support their research, thus creating more appropriate and flexible approaches to practice-based and practice-led design research, as called for by various academic design researchers (Seago and Dunne, 1997; Gray and Malins, 2004). The research methodology devised for and employed in this project has enabled me to explore and answer important research questions (chapters 6, 7 and 8). These initial questions evolved into an overall design proposition, which was demonstrated through the design brief (chapter 9) and final collections of artefacts (chapter 10). Furthermore the application of this methodology resulted in a body of knowledge that can inform and inspire other researchers and designers in the field of textile-based Wearable Technology and beyond, in regard to design context, practice and practice methodology and provides the foundation for additional work in the future (chapter 11).

Chapter 5: Exploratory sampling

As a professional designer, I consider a clear and adequate design brief prerequisite to begin the design practice and it can be difficult, both on commercial and speculative projects, to find the very starting point of practice (i.e. sketching, designing, making, sampling, testing), if the desired design outcomes have not been formulated. This was evident in the first year of the research project, when I focused on the literature and contextual research, in order to define the potential scope of this research project. I felt frustrated by the absence of any substantial design practice after over 12 months into the project and was therefore appreciative when an opportunity to initiate a phase of practice arose. As an attendee of the upcoming Smart Textiles Conference in San Francisco in April 2013, I was invited to an 'e-textiles' evening reception, which was billed as a chance to present some of the delegates' projects in a casual setting. This was the perfect opportunity to start my design practice; by producing specific samples for the event I could test some initial ideas I already had in mind. This would not only provide insights into the design and making of the samples but could further be useful to generate initial informal feedback from stakeholders in the Smart Fabrics and Wearable Technology community, in response to the created samples.

5.1 Prototype creation for Smart Fabrics 2013

In order to make the most of the design process and opportunities for feedback, I set myself a concise 'design brief':

- To create a small collection of wearable and/or demonstration samples, which could be used as a talking point during the evening reception
- To produce samples that focus on exploring substrate material choices with a particular view on biodegradability at the product's end-of-life
- To design samples that I could utilise to 'tell the story' of VOC sensing from the user's body/ skin in an understandable way
- To develop samples that could embed my identified concerns about the lack of end-of-life thinking in a positive manner, in order to inspire constructive conversations with other delegates



Fig. 5.1: OneMoment natural rubber shoe



Fig. 5.2: Liquid natural rubber latex in mould

My attention first turned to the consideration of materials and I chose to explore the potential of natural rubber. Although this was an intuitive decision based on a brief but promising experimentation with liquid rubber during a previous design project, this approach also suited my aim to investigate and develop materials that could be biodegradable at the end of the product's life. Other designers have also started to explore natural rubber as an environmentally friendly material in view of providing products with embedded end-of-life solutions, and Spanish company OneMoment launched their biodegradable shoe concept (fig. 5.1) in 2011 ^{5A}. This sock-like shoe offers a light, durable and inexpensive choice for watersports, the beach and travel, and was described as fully biodegradable, while conforming to the relevant environmental regulations.

Natural rubber is obtained from milky liquid latex found in the sap of many plants and trees and although many natural rubber products such as yoga mats, flip flops and other footwear, condoms and balloons are often described as biodegradable, biodegradability is not that straightforward. Firstly, there are different levels of biodegradability and items made from natural latex are not as quick to biodegrade as other perishable items such as food, as they need to be broken down into their fundamental particles and secondly, effective biodegradability depends on the composting facilities and environment, including factors such as surrounding materials, temperature and sunlight. However, research has shown that biodegradation in a suitable composting environment can be considered an efficient way of waste disposal for natural rubber (Ikram and Hashin, 2002) and I propose the exploration of natural rubber as a potential biodegradable substrate a worthwhile route, as it may provide new concepts for wearable sensor substrates in the future,

as knowledge of this material's suitability for composting and biodegradability continues to develop.



Fig. 5.3: Plain rubber (a and b) and rubber with natural flock (c and d) samples, Prahl (2013)

For these experiments it was important to work with liquid rubber, rather than utilising pre-manufactured natural rubber, as I wanted to be in control of the size, shape and thickness of my samples. I also needed to be able to combine natural rubber with other natural and biodegradable components, which could be added during the rubber pouring or setting stage. For the substrate, I utilised commercially available liquid natural latex ^{5B} to produce swatches, while other components included hand-made natural fibre recycled flock, including cotton, hemp, silk and wool.

I produced plain rubber swatches (fig. 5.3 a and b), and swatches combined with recycled natural flock (fig. 5.3 c and d), which was either embedded into the rubber or added to the surface, as the liquid material was solidifying. Although natural and synthetic rubber has long been used as a material that can be worn directly on the skin for products such as condoms, gloves, swimming caps and footwear, the aim was to add a natural and textured embellishment in order to create a substrate that was more similar to a traditional textile and thus, more familiar and acceptable to wear.

An important fact to note about utilising liquid latex is that drying times vary significantly depending on the studio temperature and it is therefore quicker to let the samples dry in as warm a place as possible. However, as the smell of latex is extremely strong and potentially harmful to human health due to the addition of ammonia as a preservative, it is essential to work in a ventilated room or outdoors. Another issue is the potential appearance of air bubbles as the liquid is poured into the mould, however stirring the liquid carefully or piercing the bubbles with a needle before the material dries, can avoid this problem.

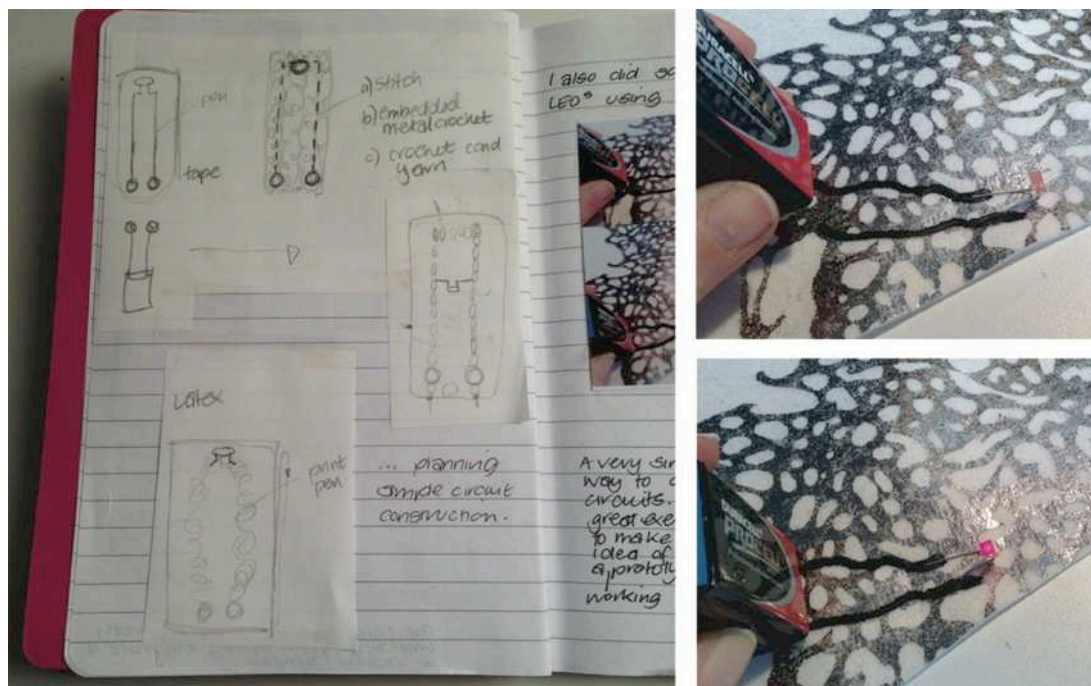


Fig. 5.4: Layout for simple circuit in sampling logbook and battery powered circuit with LED, Prahl (2013)

In addition to developing the substrate material for the prototypes, it was important to consider how the samples could become interactive for a better impact and visualisation of how the sensor would react to stimuli and I started to plan and create simple circuits (fig. 5.4), which could be utilised to simulate the wearable sensing device's reaction to VOCs from the wearer's body. I worked with a combination of printed and stitched circuits, using nontoxic, solvent free and water-soluble Bare Conductive Paint ^{5C} in a pen format and silver-coated Lame Lifesaver conductive thread ^{5D}, both of which were compatible with the rubber substrate and the circuits were completed with small coloured LEDs, which could light up through the use of a battery (see fig. 5.5).

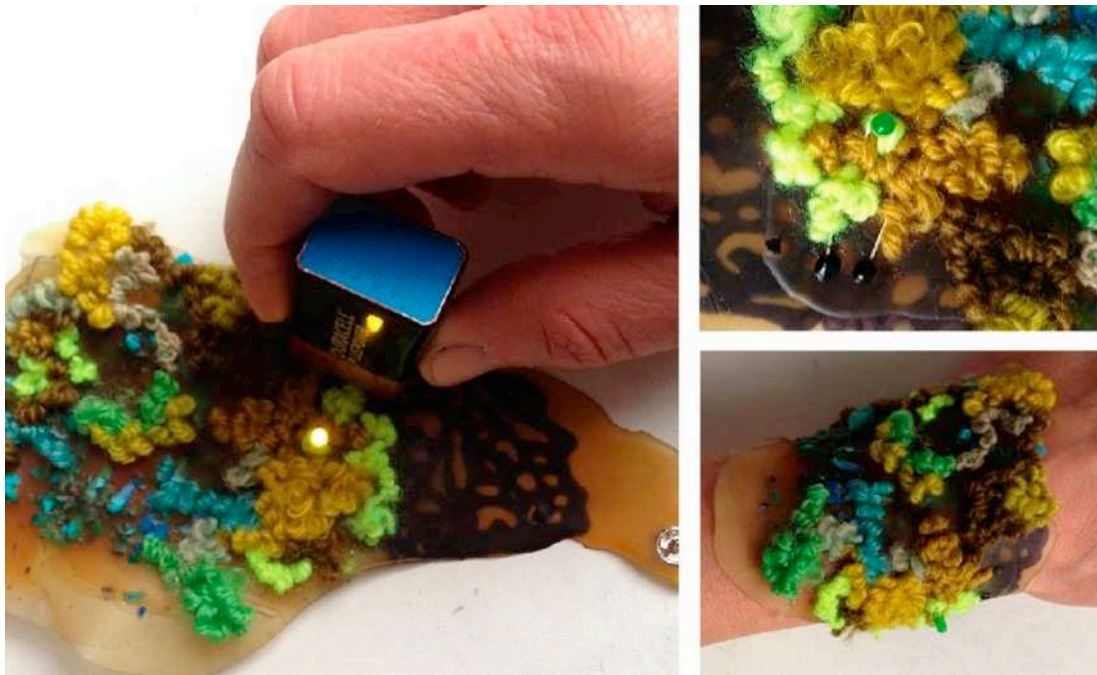


Fig. 5.5: Rubber and natural flock sample with stitched and printed circuit and LEDs, Prahl (2013)

The first wearable prototype (fig. 5.5) was made with liquid natural latex to produce an organic looking, irregular shaped piece of soft material, which was long enough to fit around the wearer's wrist and fastened with a small stitched-on snap button. The black abstract pattern simulates a generic printed sensing technology, and was printed on the next-to-skin-side to correspond with the wearer's forearm skin, one of the locations where VOCs are emitted from the body (chapter 7). Bare Conductive Paint was used to seal in the ends of the metal LED pins, and these two conductive points would be used to connect the battery, in order to light up the LED. The substrate's surface was embellished with handcrafted needle-punch stitch, using wool yarn, to provide a thick and textile-like touch.



Fig. 5.6: Rubber and natural flock sample with Aniomagic touch sensor and stitched circuit and LEDs, Prahl (2013)

The second prototype (fig. 5.6) was made with liquid natural rubber to produce a small rectangular swatch, which was embellished on the surface with recycled

natural cotton and hemp flock during the solidification process. This sample was not intended to be wearable but was created as a swatch, which could be handled to demonstrate the textile feel created by the flock surface. In order to visualise a reaction from the sensing device to either biochemical or environmental VOCs, I utilised an Aniomagic touch sensor kit ^{5E}, consisting of conductive nylon ripstop strips, Velcro and a small battery, which was stitched on and connected into a circuit with conductive thread. When the sensor on the back of the sample is pressed, the LED lights up for immediate user feedback and although I am not creating concepts for touch-sensitive wearable sensors, this was an effective way to visualise how a sensor could respond to any stimuli, including VOCs.



Fig. 5.7: Sample testing at Smart Fabrics 2013 evening reception at Obscura Digital, San Francisco

The evening reception proved to be a very informal event, held in almost complete darkness and was only scheduled to last around 60 minutes. Due to the lack of light and the casual nature of the event, this was not the time for formal note-taking, so I embraced the intimacy of the evening and simply chatted to five to six different delegates about my samples, demonstrating how they could be worn and how they would react (fig. 5.7). Despite the lack of formal data, I came away from the evening with a positive feeling about some of the delegates' interest in hearing and discussing my thoughts on the importance of developing more environmentally considered approaches to textile-based Wearable Technology design, although it became clear that this was not something they would normally consider, particularly as the Smart Fabrics Conference did nothing to address any environmental issues during the regular programme.

In order to invite further opportunities for discussion and feedback with other delegates, I also decided to wear my prototype on the second day of the conference, resulting in several casual conversations during networking breaks. I chose not to approach delegates specifically to tell them about the sample I was wearing but to let them come to me instead, which would indicate that they had noticed the sample and were interested in talking to me about it. Again, I did not utilise any formal tools to record any of the conversations in order to keep the informal atmosphere but managed to note down some key points later. The most noticeable observation was that it was mainly female delegates, as well as a female member of staff at the conference venue who approached me, while all of them commented that they had been drawn to the sample due to its use of material, colour and texture. Reflecting on the conference afterwards, I regretted that I was unable to record data during the evening and daytime conversations but also accepted that the informality of the situations and lack of formal data received, suited this stage of exploration and, although purely anecdotal, the feedback was still highly valuable for the development of my ideas and ongoing exploration and design process.

5.2 Additional sampling

Following the Smart Fabrics Conference, I continued with the design process in order to generate more samples, which could explore the development of suitable material substrates and use of colour and texture further. This natural choice of direction was where I was headed intuitively, although the decision to delve deeper into material, colour and texture was further reinforced by reflecting on the informal feedback I had received at the conference. In addition, I chose to include an initial investigation of suitable silhouettes and form factors into this stage of exploration, as I had come across some pivotal information when looking into the key locations for VOC emission from the body. I discovered that VOC biomarkers from the wearer are best measured close to eccrine sweat glands, which can be found on the forehead, upper back, neck, lower back, armpits, forearms, palms and feet and I selected the palms and forearms (fig. 5.8) as the first on-body locations to explore for new types of wearable sensor silhouettes.

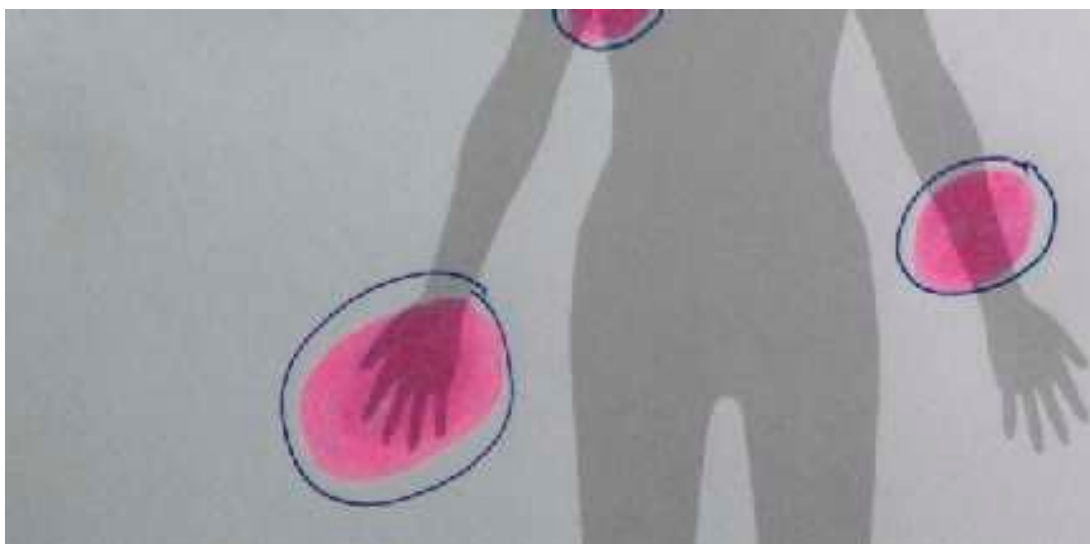


Fig. 5.8: Eccrine sweat glands including the palms and forearms, Prahl (2013)

Progressing my quest to explore end-of-life solutions for wearable sensor substrates, this stage of sampling continued to consider biodegradability as well as introducing the concept of recyclability, as two different types of substrate materials were explored.



Fig. 5.9: Natural rubber substrate with embedded wool crochet, Prahl (2013)

This first sample (fig. 5.9), which was designed as a wide wristband in order to be able to catch VOC biomarkers from the wearer's lower forearm, utilised a combination of natural rubber and wool yarn. The yarn was crocheted into a piece of material long enough to wrap around the wearer's wrist, before it was embedded into the liquid rubber substrate and once dried, the texture of the crochet left irregular holes in the rubber on the skin-side, which could be useful for extra breathability as the device would be worn next to the skin. In regard to end-of-life, as both components are natural and biodegradable, the item could be composted

without prior disassembly. However, it is highly likely that the biodegradation times of natural rubber and wool yarn would be different.

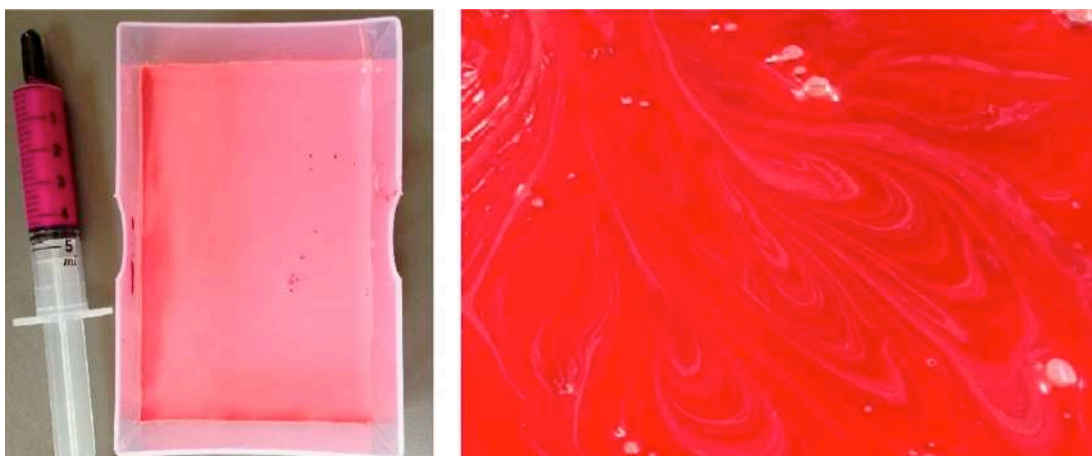


Fig. 5.10: Liquid latex coloured with thermochromic (a) and food colouring (b) pigments, Prahl (2013)

Depending on the type of liquid latex used, the milky white liquid generally dries into various shades of beige or light brown when solid and in order to explore the potential of this material beyond its natural colour, another group of samples investigated the use of colour through the addition of Dr. Oetker food colouring (fig. 5.10 b) and thermochromic (fig. 5.10 a) and photochromic pigments^{5F}. Injecting colour through stirring and dripping into the liquid created various effects, such as smooth and consistent colour or marbled effects (fig. 5.10 b) and this route may be a way to make the use of natural rubber more appealing to a broader section of users. The idea behind using food colouring was to combine colouring that is harmless, with the natural and biodegradable substrate in order to produce a product that would be environmentally benign during and following composting, while the use of reactive colours could also have interesting potential for wearable sensors, as it could provide the wearer with instant feedback or colour-changing aesthetics.



Fig. 5.11 a, b, c and d: Liquid and dried latex coloured with photochromic pigments, Prahl (2013)

The samples above show the use of photochromic magenta pigment, which was dripped into the liquid latex to create a marbled pattern (fig. 5.11 a). Once the natural rubber had dried into solid material and was exposed to UV light, the pink pattern intensified to a much brighter shade of magenta (fig. 5.11 b-d). Although UV exposure is not relevant to VOC biomarker sensing from the wearer, it could be utilised as a decorative feature for environmental VOC sensing, or could simply visualise a potential response mechanism to VOCs, in the absence of functional technologies to work with.



Fig. 5.12 a, b: Natural rubber coloured with food colouring and surface embedded natural flock, Prahl (2013)

Use of colour and texture was noted as an important feature following feedback from Smart Fabrics 2013, and this sample (fig. 5.12 a) explored the added substrate

colour in combination with colour and texture added through surface flocking. Wool, cotton and hemp flock was carefully applied to the liquid surface during the drying process (fig. 5.12 b), in order to create a textile-like feel and aesthetic appeal. Care had to be taken with the exact timing of the application of flock, as the surface had to be sticky enough to securely embed the flock, without covering it in the liquid rubber, which would result in the soft flock fibres turning hard. These experiments with colour and texture also showed that the natural appearance of rubber could be transformed into something potentially more appealing to the user.



Fig. 5.13: Bioplastic coloured with food colouring and surface embedded natural hemp flock, Prahll (2013)

Another interesting biodegradable substrate material is bioplastic, although, as with natural rubber, there are potential biodegradation issues, due to the lack of suitable facilities and services and the need for the perfect conditions during the composting process. Other concerns about bioplastics include the use and wastage of food crops, such as maize, wheat and sugarcane, which can be utilised to produce the material, and it is often discussed that the manufacture of bioplastics could contribute to the global food crisis. However, as part of this conceptual exploration, I feel it is a valid approach to investigate if bioplastic materials could be suitable, in particular in view of creating cost-effective and disposable wearable sensing products. I therefore experimented with producing a studio-made version of bioplastic, utilising glycerine, white wine vinegar, corn starch, baking powder and food colouring, which was further embellished with hemp fibre flock to add a textured surface (fig. 5.13). Several hours of drying time in the oven turned the soft, thick liquid into a rubbery, leather-like and see-through substrate, which was pleasant to touch. Although this batch of material tore easily, it would be possible to

make the material more durable following further experimentation with ingredients, composition and drying methods.



Fig. 5.14: Melissa thermoplastic shoe



Fig. 5.15: Silicone rubber material

My attention was further focused on investigating potential substrate materials that could be recycled and I was inspired by Brazilian brand Melissa, who produce shoes that are made entirely from Melflex (fig. 5.14), a thermoplastic material that can be melted down at the end of the product's life to create raw material for a new model, or potentially, other products ^{5G}. Although I had no access to this type of soft, mouldable thermoplastic, I chose to work with a commercially available, nontoxic, hypoallergenic, mouldable and two-part silicone rubber ^{5H}, which highlighted the potential of utilising soft synthetic materials, which, at the end of the product's first life, could be reclaimed and recycled through chemical or thermal recovery, to be remanufactured into new products. This material has a curing time of three minutes and therefore needs to be worked with quickly (fig. 5.15). The main attraction of this product was that it is easy to work with as part of a studio practice and can be moulded around body parts to achieve a good fit, while producing a soft and highly flexible material, which would be suitable to be worn next to the skin for limited periods of time.



Fig. 5.16: Silicone rubber and polyester crochet hand-worn sensor prototype, Prah (2013)

Palms could be a suitable location for measuring VOC biomarkers from the wearer and I therefore developed a hand-worn prototype (fig. 5.16), which utilised the soft silicone rubber in the palm area, where a printed sensing technology would enable the monitoring of VOCs, and a crocheted part on the back of the hand to create a more textile-like aesthetic and feel. The sample proved to be extremely comfortable to wear, as the silicone rubber palm had been moulded around my own hand and therefore fitted like a second skin and was flexible enough for basic hand movements. However, such an item could only be worn for specific periods of time, as it would restrict the user during many types of activities and could get sweaty without any in-built ventilation in the palm.



Fig. 5.17: Silicone rubber wristband with cotton and bamboo needle-punch and embedded LED, Prah (2013)

The silicone rubber wristband (fig. 5.17) was inspired by the growing popularity of wristband activity trackers, such as Nike+FuelBand, Fitbit and Jawbone UP (Chapter 2) but was concerned with providing a more flexible and softer alternative to the hard plastic that is often used for such devices. Thanks to the nature of the pliable material, the wristband was moulded around the wrist, which enhanced comfort and fit during wear. I first stitched a conductive circuit directly into the substrate and attached the LED, which could light up when connected to a battery through the stitched circuit, before embellishing the substrate with thick handcrafted needle-punch stitch to provide a warm and soft textural surface. In order to sense VOCs from the wearer's inner forearm or wrist, the device would also need to be enabled with an available printed sensing technology.

When designing recyclable products, there are several aspects that need to be considered and these include the choice of materials, components and joining methods in order to enable successful and cost-effective disassembly for reuse and remanufacture. In commercial products, mono-material construction, such as the thermoplastic Melissa shoe shown in fig. 5.14 would be preferable, as it is easier to recycle a product made from one type of material only. These considerations extend beyond the substrate material, as the same scrutiny needs to apply to any threads or yarn utilised as embellishment. Therefore it is preferable to utilise embellishment that works on the same principles as the material substrate; natural threads can be used within biodegradable concepts, while synthetic threads could be recycled.



Fig. 5.18: Considering disassembly for devices made with heterogeneous materials, samples (a and b) and sketches (c), Prahl (2013)

However, when combining heterogeneous materials and components, as is the case with the two prototypes described above (fig. 5.18 a and b), it is essential to keep disassembly in mind during the design phase (fig. 5.18 c), in order to facilitate recycling and remanufacture without downgrading the materials and subsequent products in their next life and this would need to be considered through the use of impermanent and easy-to-disassemble joining methods and connections when designing any further prototypes and concepts. The hand-worn prototype described above, is equipped with a simple mechanism for disassembly, as it utilises four holes on either side of the silicone rubber part (fig. 5.18 b), so that the crocheted top panel can be easily attached and detached through the use of a simple stitch. Working with homogeneous materials is also important when designing biodegradable concepts and prototypes (fig. 5.18 a), as in order to enable environmentally benign and effective decomposition, these items must not contain any hazardous chemicals and are easier to biodegrade if the various components and materials used have similar decomposition times and environmental requirements, such as temperature and light. An alternative would be to design biodegradable wearable sensors with disassembly in mind, so any non-biodegradable components can be extracted before the substrate goes into composting facilities. However, this route is unlikely to be cost-effective for disposable products unless the disassembly mechanism can be very simple.

Most wearable sensors need electronic components to enable sensing, potential user feedback and data transfer and it is therefore essential to consider these enabling components and technologies with the same scrutiny. The interactive prototypes produced during this stage of exploration contain conductive stitching, batteries and LEDs, all of which can be disassembled by unpicking the stitching, however it will be necessary to consider how this will affect the design of the conceptual wearable sensor collection, as these concepts are intended as potential inspiration beyond the realm of studio-practice, i.e. they need to consider how disassembly for reuse, recycling and remanufacture could be approached for commercially viable sensing products.

5.3 Conclusion

This long-awaited stage of practice proved to be a critical stage of the journey, which subsequently led to the development of the project's design focus. Based on my professional practice I was able to tap into tacit knowledge of relevant end-of-life design strategies, which during this process of exploratory creation, naturally integrated into the design process. This phase of spontaneous and intuitive sampling resulted in the generation of diverse, qualitative data including sample swatches, prototypes and a logbook, as well as anecdotal stakeholder feedback on a small collection of prototypes. Furthermore, the preparation and presentation of my paper 'Wearable bio-sensing for wellbeing: A material-driven design exploration' (Prahl, 2013) at the LCF Textiles Symposium in July 2013, gave me the opportunity to further reflect on the outcomes, providing valuable insights into the critical connections between material, form and function.

The generated data has been highly valuable in developing the next steps of the design research journey and was instrumental in the conception of the three-stranded investigation into *material*, *form* and *function*, as part of the next research and practice stage (chapters 6, 7 and 8). In particular, I gained valuable insights into various aspects of material substrate, circuit and form factor design, which informed and inspired the next steps of practice, while also developing a new understanding of the importance to plan, prepare and document any interaction with stakeholders and potential users, in order to evaluate and document the generated data adequately.

Chapter 6: Material substrates for wearable sensors

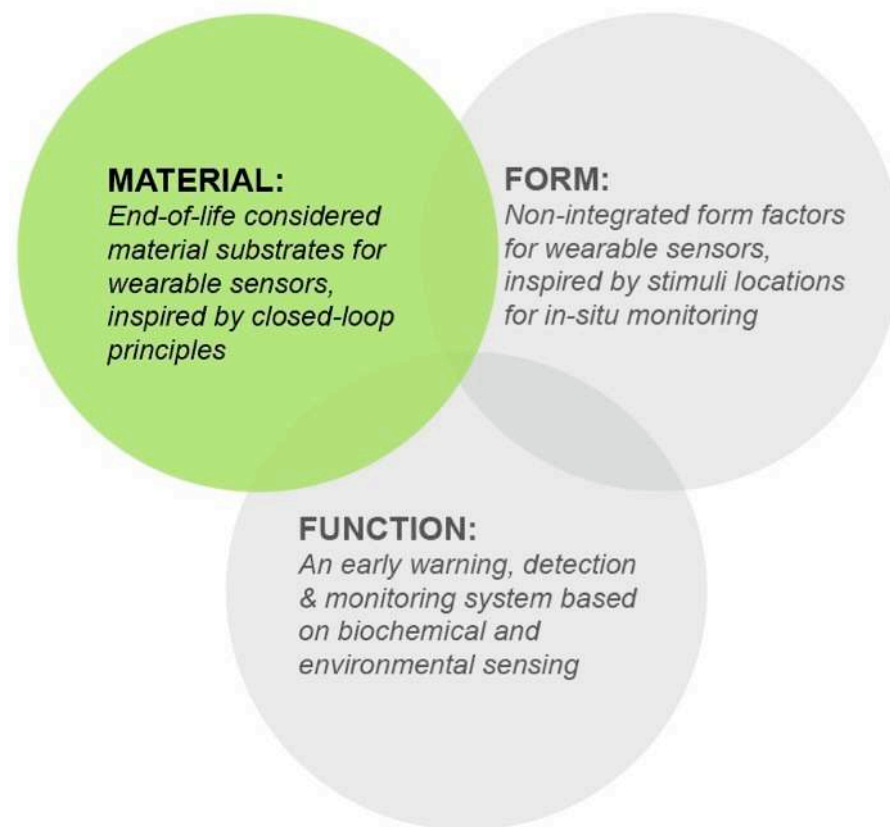


Fig. 6.1: Diagram showing MATERIAL focus as part of three-stranded investigation, Prah (2015)

Chapter 2 highlighted emerging material developments from other sectors, such as flexible, plastic and paper electronics and sensors, and these could inspire innovation for future wearable sensor substrates, which can be produced in a cost-effective manner and provide suitable substrates for printed sensing and enabling technologies. Furthermore, the consideration of end-of-life issues should be a critical aspect of the development of future electronic textile-based Wearable Technology (chapter 3) and the scrutiny of existing, and development of new types of materials in this field, are viewed as a key opportunities (Köhler, 2013; Ossevoort, 2013). In addition, this research suggests that non-integrated wearable sensors (chapter 7) could inspire the development of end-of-life considered design concepts, as these removable and reusable sensors will provide far greater flexibility on the types of materials that can be utilised, than the conventional selection of textiles generally associated with clothing.

Inspired by the identified gaps in knowledge (chapter 3) and initial exploratory design practice and outcomes (chapter 5), the design research investigation

developed into three individual but firmly linked strands; 'Material', 'Form' and 'Function' and this chapter presents the design practice and research activities undertaken as part of the 'Material' investigation.

6.1 Material driven end-of-life solutions

While initial sampling loosely explored the concepts of biodegradability and recyclability for material substrates (chapter 5), this particular investigation of material substrates aims to naturally integrate the consideration of end-of-life solutions into the design process. Indeed, the role of the designer is critical in the pursuit of end-of-life solutions for concepts, developments and commercial products, as Lombardi (2006), Executive Director at Eco-Cycle International, pointed out the compelling link between design and waste:

"Waste is the result of bad design... The concept of zero waste leads upstream to the designer's desk, where waste needs to be designed out."
(Eric Lombardi, 2006)

With a view to the broader context of Wearable Technology, an industry that could be accused of contributing to the rapid growth of electronic waste, as well as the creation of the potential new waste stream of electronic textiles, any new and innovative design concepts should embrace the opportunity to *design out* any future waste as part of the design process. This approach was explored in an exhibition entitled 'Trash Fashion: Designing out waste' at the Science Museum in London in 2010 ^{6A}, which showcased how design and technology can enable the creation and considered manufacture of waste-free fashion.

The concept of design-driven innovation seems particularly relevant in light of the understanding that substantial environmental impact of a product is determined at the design stage, an important notion highlighted by academic researchers and authors in the field of sustainable design, Tischner and Charter, who argued that *'...the product design and development phase influences more than 80% of the economic cost connected with a product, as well as 80% of the environmental and social impacts of a product, incurred throughout its whole lifecycle'* (Tischner and Charter, 2001, p. 120). Chris Sherwin, Head of Sustainability at London based design and innovation consultancy Seymourpowell, believes that one of the key

challenges of sustainable design is to get sustainable thinking into the design process, so it can simply become a part of the way designers work (2012). This approach very much reflects my own attitude as a professional design practitioner, which is based on the understanding that designers need to consider the significant impact their early design decisions can have on the entire lifecycle of a product. The development of future wearable sensor material substrates therefore needs to embrace the crucial role design has to play, so that, as argued by Jonathan Chapman (2005, 2012), environmentally aware design practice can be naturally embedded within the design process, simply as an essential element of 'good design'. Design is central to the process of product development, manufacture, use and even end-of-life and the majority of design decisions have a significant impact on all the steps and stages in a product's lifecycle; the opportunity for the integration of environmental thinking and practice into the early stages of the concept and design process is therefore absolutely critical to this project.

Indeed, one of the most promising starting points for any designer wanting to reduce environmental impact and improve resource efficiency, should be to carefully consider any materials, textiles and components they choose to work with and this approach is already being explored by many designers and manufacturers, from academic research and independent designer makers to large global businesses. Sandy Black (2008, p. 109), Professor of Fashion and Textile Design and Technology at London College of Fashion, University of the Arts London, believes that '*One of the most important decisions a fashion designer has to make is what cloth to use in the collections*' and suggests that, while until recently a designer's material choices were mostly driven by aesthetic criteria rather than potential sustainability credentials, the focus is now shifting towards designers taking responsibility for gathering information and knowledge in order to achieve more environmentally and ethically considered clothing. This shift in responsibility now goes much further than designers' awareness and selection of sustainably manufactured commercially available textiles, as we can observe much activity in the field of design-driven sustainable material and textile innovation. From specific design courses, such as the MA Textile Futures (now Material Futures) at Central Saint Martins, University of the Arts London, to independent designers, to global brands like Nike; exploration, development and future implementation of new materials and their manufacturing processes is the focus of many research projects, commercial material developments and initiatives alike.



Fig. 6.2: BioCouture grown material

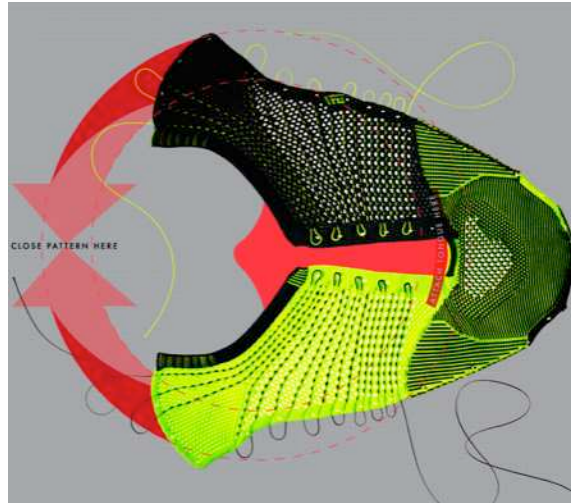


Fig. 6.3: Nike Flyknit technology

As part of her ongoing research, Suzanne Lee, Director of the BioCouture Research Project ^{6B} created a leather-like material that is manufactured through a fermentation method based on growing bacterial cellulose in order to provide compostable and biodegradable textiles suitable for clothing (fig. 6.2) and footwear. Her work has since inspired many designers to explore and create their own environmentally considered materials and textiles. On a global and corporate scale, Nike have been at the forefront of material innovation in the field of sports clothing and footwear, combining the need to create more resource efficient and environmentally considered materials with the design of high-performance products; the Nike Flyknit technology (fig. 6.3) reduces waste as the shoe upper is knitted in one piece, thus only producing the material needed, while providing the athlete with light, yet supportive and form-fitting sport shoes. Nike's efforts are part of a range of initiatives described as a 'manufacturing revolution', which puts the emphasis on exploring and reformulating how products are made and what materials they use (Barry, 2014). Along with NASA, the U.S. Agency for International Development and the U.S. Department of State, Nike are also founder members of the LAUNCH initiative ^{6C}, which is a global innovation platform to address the sustainability of materials and their manufacturing processes through closely working with material, manufacturing and service innovators. In addition, Nike developed the Nike Material Sustainability Index ^{6D}, a tool which is aimed at designers to enable more informed material selections and was further tested in collaboration with fashion students from London College of Fashion, University of the Arts London, to develop and communicate the index ^{6E}.

6.2 Closed-loop design approach

Based on the identified importance of opportunities around material innovation and my interest in conceptual textile design, this material investigation aims to address end-of-life issues through the design process, in particular the early stages of explorative material choice and textile design and making. This investigation is inspired by Cradle-to-Cradle (C2C) or closed-loop design principles. The phrase C2C was first coined by architect Walter R. Sahel in the 1970's, before being further refined and popularised with the design community in 2002, when chemist Michael Braungart and architect Michael McDonough published their book *Cradle to Cradle: Remaking the Way We Make Things*. According to McDonough and Braungart (2003), C2C design is inspired by the model of the two closed-loop nutrient cycles of nature, the biological metabolism and the technical metabolism, which create no waste. The key practical element of the C2C design principles is the categorisation of all materials into 'technical' nutrients, which can be used, recycled and remanufactured into new products of the same or higher value in continuous cycles, or 'biological' nutrients, which can be returned to the soil, where they decompose while providing nutrients, without causing any negative impact on the environment. In general, closed-loop design is a design principle, based on the understanding that all components used in the manufacture of a product should be reused, remanufactured or recycled into new products or composted, at the end of the product's life, thus enabling the reduction and elimination of waste and consequent burden on the environment.

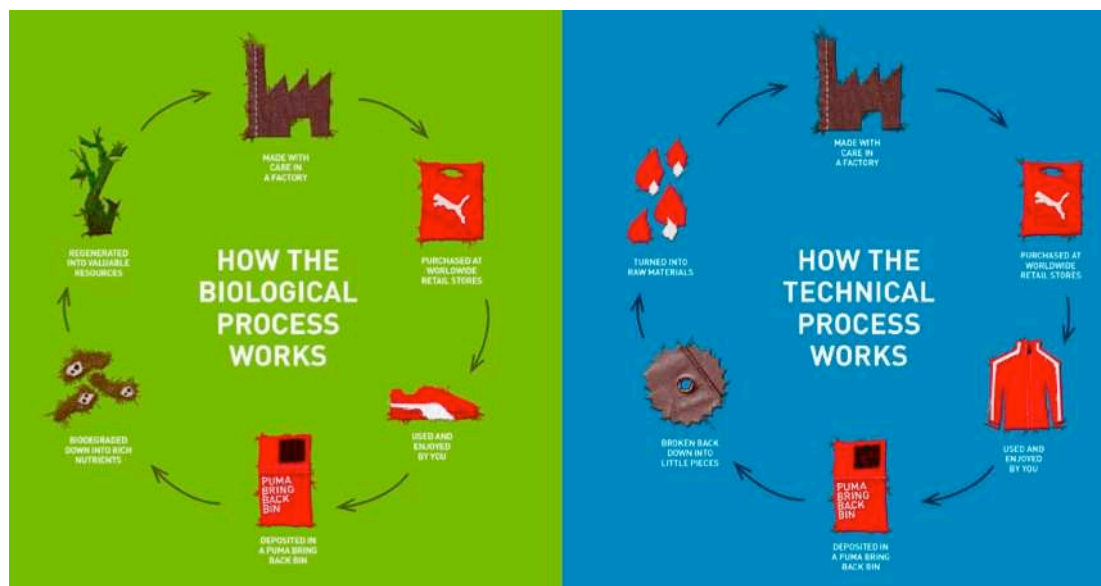


Fig. 6.4: Puma InCycle process diagram

In 2013, PUMA brought these design principles to life with their InCycle clothing, footwear and accessories collection ^{6F}, which is 100% Cradle-to-Cradle Basic certified and can be returned to PUMA stores at the end of the products' life (fig. 6.4). The collection includes biodegradable footwear, which is shredded and transported to a composting facility system, where the organic cotton upper and bio-plastic soles will break down naturally, without harming the soil, and a recycled and recyclable track jacket, that can be shredded and manufactured into polyester granulate, to provide a secondary raw material to create new products. One of the original commercial pioneers of such closed-loop thinking in the textile & clothing sector, was Japanese company Teijin Fibers Limited, who developed the first chemical closed-loop polyester recycling technology; ECO CIRCLE, in 2002, and the system has since gone from strength to strength, as the company has been working closely with apparel and sportswear manufacturers, who share Teijin's commitment to protecting the environment. The technology offers dramatic waste reduction, while further reducing both energy consumption and CO2 emissions significantly when compared to the production of virgin polyester ^{6G}.

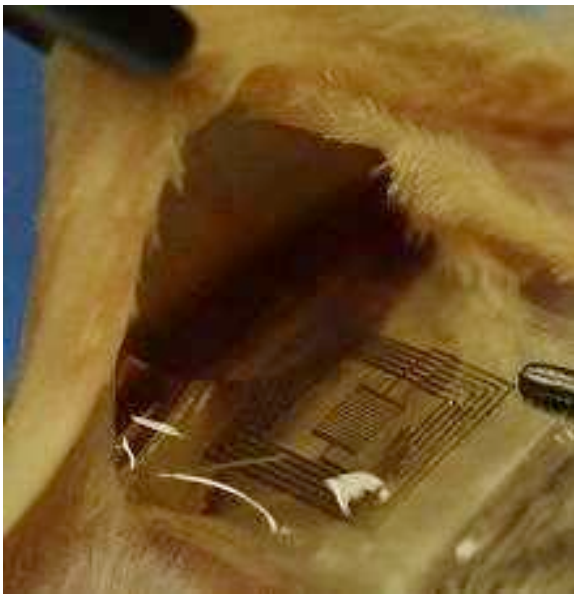


Fig. 6.5: Biodegradable 'transient' electronics

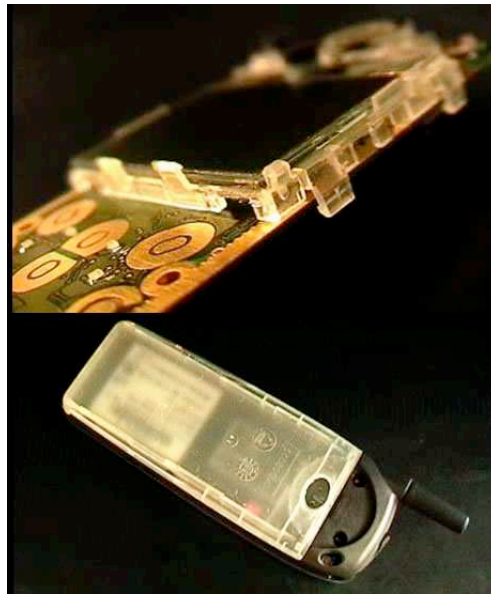


Fig. 6.6: 'Active disassembly' for mobile phones

Looking at the field of electronics, we can also observe research into the closed-loop design approach, although most of these developments are not yet ready for commercial applications. The University of Illinois turned the concept of longer-lasting electronics on its head, as scientists developed biodegradable, so-called 'transient electronics' ^{6H} that dissolve at the end of their life (fig. 6.5). These types of electronics include biocompatible electronic devices that could dissolve at a prescribed time or on command inside the body (i.e. medical applications) or in the

environment and could therefore lead to reducing the amount of consumer electronics going into landfill, while being more environmentally friendly in their production through the utilisation of bio-based, renewable materials and components. At the other end of the spectrum, research and development activities into the use of long-lasting and valuable technical components, which could be recovered for remanufacture into new products include inspiring examples from the field of mobile phones. Several projects investigate and develop processes such as ‘active disassembly’ (Chiodo, Billet and Harrison, 1999) and ‘triggered degradation’ (Scott, 2014), which could potentially enable disassembly (fig. 6.6) and reuse of the various elements, to be manufactured into new products as part of a closed loop strategy.

As electronic textile-based wearable sensors products fall in between the categories of textiles & clothing and electronic consumer goods, they can be described as hybrid products. It is therefore essential to be aware of developments in both fields, in order to understand and anticipate issues and opportunities across both product categories, as well as the consequences of bringing these product types together into one. Inspired by the closed-loop principle in general, this particular investigation therefore aims to design and develop material substrates that could be utilised to create devices that can be recycled into new products or disposed of safely without any negative environmental impact, at the end of their first life, thus exploring opportunities for both *recyclable* and *disposable* wearable sensor concepts.

The research question driving this stage of the investigation, including the design and making of samples and further research into existing substrates, as described in the following sections of this chapter, can be summarised as:

- Can a closed-loop approach to material substrate design inspire new concepts for wearable sensors?

6.3 Designing material concepts

Inspired by closed-loop/ C2C design principles, and with the aim to explore whether these principles could inspire the design of new wearable sensor material substrates, I embarked on an intuitive yet deliberate design and making phase. In particular this involved the creation of two distinctive material concepts, comprising a collection of

visual and tactile materials collated onto boards, to convey the design narrative. These concepts investigate the use of biological and technical raw materials, and further explore the use of two different manufacturing or making processes (nonwoven and constructive), in order to create diverse aesthetics, surface interest and end-of-life options.

The first concept; '*Skin-tech*' was inspired by nonwoven material sampling and making methods, considering the use of both technical and biological raw materials (fig. 6.7), in order for the material substrate to be recyclable or biodegradable at the end of its first life, while the second concept; '*Tecrochet*' was inspired by constructive material sampling and making methods, also working with both technical and biological raw materials (fig. 6.7), in order to provide recyclability or biodegradability at end-of-life.

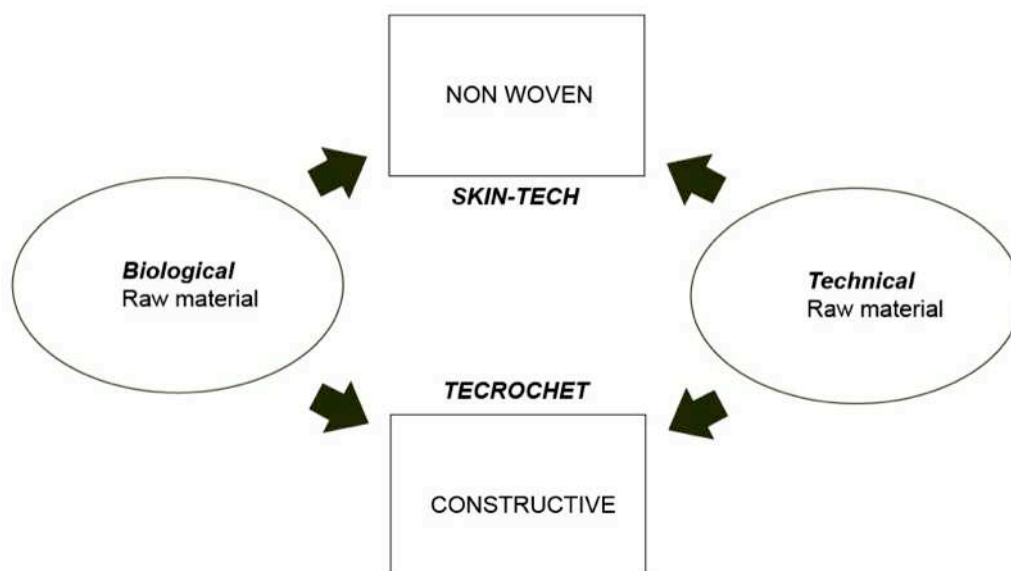


Fig. 6.7: Design strategy for two material concepts: Skin-tech and Tecrochet, Prah (2013)

6.3.1 Skin-tech

Although the conception of the 'skin-tech' concept was partly driven by my personal interests and material preferences, based on my initial experimentation with both natural and silicon rubber, it was mainly inspired by the desire to build on the promising research and development in the field of flexible and skin-like electronics, such as tattoos, patches and plasters (chapter 2), most of which utilise innovative material substrates manufactured through nonwoven technologies. Although

technically groundbreaking, most of these developments currently lack aesthetic appeal, as they are primarily intended for medical and health applications and often conceived and developed by scientists, engineers and other technical disciplines, who are not generally experienced with designing materials and products for a broader lifestyle use. With the development of this concept, I therefore aimed to push aesthetics, tactility and use of colour, based on the understanding that these designed artefacts, including mood boards and swatches, could potentially inspire developments in the emerging field of flexible and stretchable electronics for wearable sensor materials in the future.

Skin-tech: second skin-growth-decay-surface texture



Fig. 6.8: Skin-tech mood board using secondary and primary research images, Prah (2013). Clockwise: (a) Allergic skin reaction to henna tattoo, (b) natural flock print, Prah (2009), (c) epidermal electronics, (d) scar bodice, BioCouture, (e) J Smith ESQ, (f) carpal skin, Neri Oxman.

The first step in the creation of this concept was to produce a visually inspiring mood board (fig. 6.8) that could bring together key references and express my vision for the direction of the material substrates in terms of appearance, feel and texture. The concept included the elements of second skin, growth, decay and surface texture and these references were collected much in the same way I would approach a commercial design project, such as secondary research in magazines and the Internet, as well as utilising trend forecasting website WGSN ⁶¹. In addition, I had already produced diverse textile samples and swatches in the initial explorative

stage of the project (chapter 5), which subsequently became part of the inspiration process for the design of these two material concepts.

Following the visual formulation of the mood board, I embarked on an intuitive sampling process, which produced a diverse range of swatches, informed by my original design strategy of utilising biological and technical raw materials, as well as the images used in the mood board. I naturally gravitated towards utilising biological elements to produce the substrate samples, which utilised liquid or mouldable raw materials latex and bioplastic and were formed or cut into shapes, as well as the process of needle-felting a range of natural fibres (banana, soya bean and Tencel) into a loose type of nonwoven felt (fig. 6.9 a-c). Naturally dyed bioplastic substrates were also combined with recycled naturally dyed bamboo flock and needle-felted soya bean fibre (fig. 6.9 d-e), while food-coloured latex was embedded with bamboo fibre and combined with a banana fibre needle-felted surface (fig. 6.9, g-i). This method was carried on from the explorative sampling stage (chapter 5), with the aim of providing the wearer with comfort and a more textile-like surface and appearance, while keeping the latex or bioplastic substrate next to the skin, where it would be printed with an enabling sensing technology for direct skin contact. Although this means that two different natural materials are combined into one substrate, it will remain biodegradable even though biodegradation times of the two components may vary.



Fig. 6.9: Selection of biological material swatches, Prahl (2013): (a) Needle-felted banana fibre, (b) needle-felted soya bean fibre, (c) needle-felted Tencel fibre, (d, e) bioplastic and bamboo flock, (f) bioplastic and soya bean fibre, (g, i) latex with embedded bamboo fibre, (h) latex with needle-felted banana fibre.

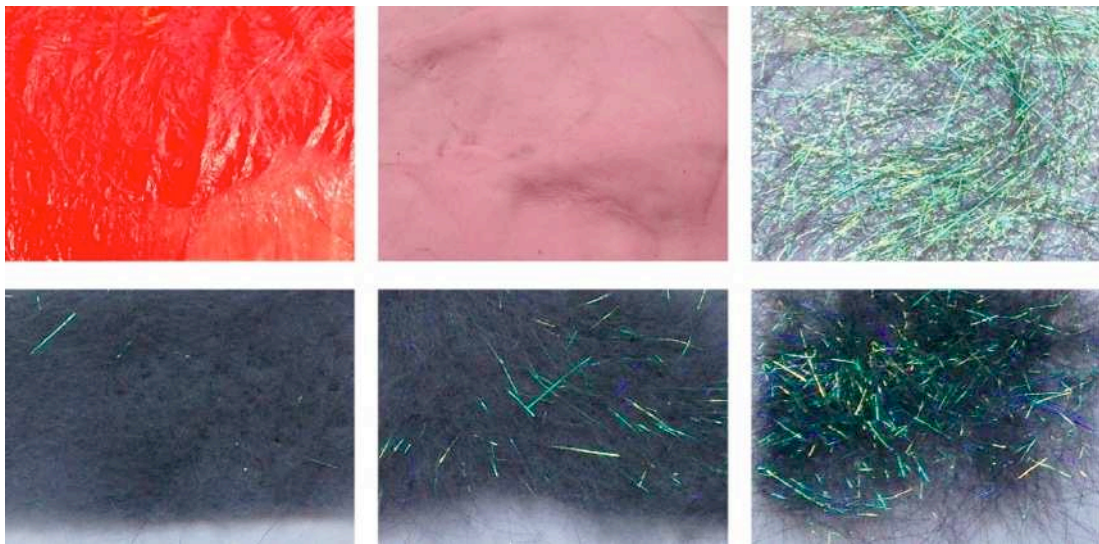


Fig. 6.10: Selection of technical material swatches, Prahl (2013): (a) Plastic, (b) silicone rubber, (c) synthetic heat-bond fibre, (d) needle-felted polyester, (e, f) needle-felted polyester and synthetic heat-bond fibre.

Wearable sensor substrate swatches based on technical materials utilised mouldable plastic and silicone rubber (fig. 6.10 a, b), as well as heat bondable synthetic fibre (fig. 6.10 c), while needle-felted swatches were made with polyester

fibre (fig. 6.10 d), and a combination of polyester and heat bondable synthetic fibre (fig. 6.10 e, f).



Fig. 6.11: 'Second skin' board, primary and secondary images and swatches, Prah (2013). Top row inspiration: (a) micro'Be fermented material, (b) bio plastic sample Prah (2013), (c) Fabrican spray-on material, (d) bottom row hand-made samples: Thin and flexible latex and bioplastic swatches, Prah (2013).

In order to present and evaluate some of the key swatches in a visually inspiring manner, I categorised them into three material trend groups in order to highlight the diverse aesthetics and material compositions, which could be used to inform the next steps of my design enquiry, as well as potentially be shared with other designers and researchers in the future. Samples generated in the 'Second skin' group (fig. 6.11) are lightweight and slightly see-through to mimic the appearance of skin, while 'Fused Encapsulation' samples (fig. 6.12) explore the inclusion of natural fibre embellishment, which is integrated onto the latex surface or embedded into the latex substrate, and samples in the 'Melted layers' group (fig. 6.13) are concerned with the addition of strong colour, either through infusion into the liquid latex or by adding recycled latex cuttings to the surface during the drying process.

FUSED ENCAPSULATION



Fig. 6.12: 'Fused Encapsulation' board, Prahl (2013). Top row inspiration: (a) cardboard cellulose nonwovens VTT Finland, (b) latex encapsulated flock sample Prahl (2013), (c) Cosyflex latex cotton, (d) bottom row hand-made samples: natural fibre embellished latex substrates Prahl (2013).

MELTED LAYERS



Fig. 6.13: 'Melted layers' board, Prahl (2013). Top row inspiration: (a) marbled colour latex sample image, Prahl (2013), (b) POP magazine S/S 2011, (c) WGSN global materials direction S/S' 15, (d) bottom row hand-made samples: colour infused latex substrates, Prahl (2013).

6.3.2 Tecrochet

In addition to the nonwoven route, I was keen to explore a constructive material approach to offer potential for strategic disassembly, which is an essential part of designing for end of life in order to be able to reclaim and re-use materials for remanufacture into a new material or product. In addition, this method would create a very different look and feel and I selected crochet as a suitable method of construction, in order to explore the contrast of the hand-made and technical aesthetics by proposing the use of more unconventional yarns and materials into the process.

Tecrochet: tradition/ future-hippy/ tech-delicate/ chunky



Fig. 6.14: Tecrochet mood board using secondary research images, Prahl (2013): (a) knitted art by Magda Sayeg, (b) Elena Corchero solar textile, (c) Nike Flyknit knitted upper, (d) crochet pressure sensor by kobakant, (e) Shapeways 3D-printed bikini, (f) Valentino S/S 2012.

The ‘tecrochet’ mood board blended aspects of contrasting features including ‘tradition/ future’, ‘hippy/ tech’ and ‘delicate/ chunky’ and the featured secondary research references were gathered from magazines, the Internet and trend forecasting website WGSN and as before, the mood board served as an inspiration for the subsequent process of sampling and material ‘trend group’ creation. However, based on the insights into the design process of the first concept and in

order to encourage inspiration from the start, this time I intuitively worked into material trend groups straight away, instead of producing swatches first.



Fig. 6.15: 'Second skins' board, Prah (2013). Top row trend inspiration: (a) Nike Flyknit running shoe, (b) Nike seamless knit, magazine image, (c) bottom row hand-made samples: various crochet swatches utilising biological and technical yarns, Prah (2013).

Samples generated in the 'Second skins' group (fig. 6.15) were inspired by high-tech performance footwear and sportswear clothing, and utilised delicate wool paper, bamboo, cotton, Japanese paper and raw silk, metallised polyester/ viscose and recycled plastic yarns for a micro- structure. 3-D printed materials and products inspire the second group, 'Future yarn' (fig. 6.16), which produced samples with a variety of biological and technical yarns, including flexible rubber, latex coated cotton, waxed cotton, jelly and plastic, while the third group 'Tech coating' (fig. 6.17) explored the combination of latex and crochet using backed, rubberised, embedded and coated finishes to produce latex-embedded cotton crochet, latex-embedded wool paper crochet, latex-dipped Japanese paper & raw silk crochet, latex-embedded recycled silk, cotton and viscose crochet, latex-dipped multi-coloured bamboo crochet and latex-coated silk/ cotton crochet.

Future Yarn



Fig. 6.16: 'Future yarn' board, Prah (2013). Top row trend inspiration: (a) WGSN global material direction S/S 15, (b) plastic net photograph, Prah (2013), (c) wool thread dipped in tar and latex by Sandrine Pelletier, (d) bottom row hand-made samples: various crochet swatches utilising biological and technical yarns, Prah (2013).

Tech coating



Fig. 6.17: 'Tech coating' board, Prah (2013). Top row inspiration: (a) coated knitted gloves, (b) latex-backed crochet sample A. Prah, 2013, (c) WGSN global material direction S/S 15, (d) bottom row samples: various latex-coated crochet swatches utilising biological yarns, Prah (2013).

6.3.3 *Material concepts evaluation*

This practice-based material investigation produced a range of mood boards, swatches and material trend boards, all of which were primarily intended to inform and inspire my own design practice as part of the investigation but could also be shared with other designers and researchers in the future to inspire new ideas, developments and collaborations. Furthermore, it can be noted that although I had a focused design strategy as a creative framework, I also allowed myself to be led by intuition during the design and making of the mood boards and swatches. The concept of working with closed-loop design principles was intended to inform and stimulate this element of practice rather than restrict it.

Specifically, the process of designing and creating mood boards, swatches and material trend boards highlighted a range of observations and generated a collection of artefacts, which contributed to planning the next steps of design research and practice. My fascination with latex as a raw material was apparent from the samples I created, as the material featured heavily in both concepts (fig. 6.18 and fig. 6.19). While this was not an issue, I had to be aware that I might need to consider other nonwoven materials in order to enable a more exhaustive investigation of potential raw materials. I also recognised that I was naturally drawn towards the use of biological materials, somewhat neglecting the exploration of technical yarns and substrates, and realised that if I wanted to pursue the concept of working with technical, and therefore recyclable materials and substrates, my design practice would need to incorporate the use of technical raw materials going forward. Following the evaluation of both concepts, I decided that the nonwoven approach was the route I wanted to pursue for the remainder of the project and this is reflected in the subsequent stages of my design research.



Fig. 6.18: Selection of 'Skin-tech' samples, Prahl (2013). Latex with natural fibre embellishments, needle-felted layers and inclusions.



Fig. 6.19: Selection of 'Tecrochet' samples, Prahl (2013). Synthetic and natural crochet with latex coatings and layers.

6.4 Additional material research & sampling

Inspired by the outcomes of the material exploration, I appreciated that there were specific aspects I needed to explore further in order to develop the final material focus for the formulation of the design brief and the subsequent design of the wearable sensor collection. I therefore entered a phase of design research, which comprised an in-depth overview of commercially available wearable material substrates, a user workshop with a particular focus on preferences for body-worn materials, an additional phase of material sampling and making, and some basic, on-body material testing.

6.4.1 Wearable substrates overview

In addition to the creative exploration of the material stories '*Skin-tech*' and '*Tecrochet*', which had been very much an intuitively driven investigation focusing on design inspiration with regard to aesthetics and tactility, it was further essential to undertake some more systematic research, in order to generate diverse and relevant data, which could contribute to the formulation of the design brief. I therefore embarked on an overview of commercially available medical, health and beauty products, which utilised a broad selection of wearable, low-cost, disposable and reusable material substrates. I was positively surprised at the variety of available products and their diverse range of innovative materials, all designed to comfortably sit on the wearer's body and skin, often utilising skin-friendly adhesives to be attached to a particular part of the wearer's body securely.

Depending on the location on the body and area of skin where these medical, health and beauty product are worn, a broad range of materials is utilised to create comfortable and form-fitting 'wearables', which can be designed for single, multiple or long-term use. In the context of this research, wearables refers to any items that can be worn (i.e. on the skin, on the body or inserted/ attached to an item of clothing, accessory or footwear) and include both technical and non-technical items. However, this overview focuses on a range of materials that can be divided into four categories: 'rubber-like', 'textile-like', 'paper-like' and 'film-like'.

Rubber-like



Scholl ball of foot cushion



Superdrug soft gel bunion protector



Undercover Glamour nipple covers



Scholl Party Feet sore spots



Gold-Bio-collagen face mask



Scholl Party Feet gel cushion



Big toe straightener

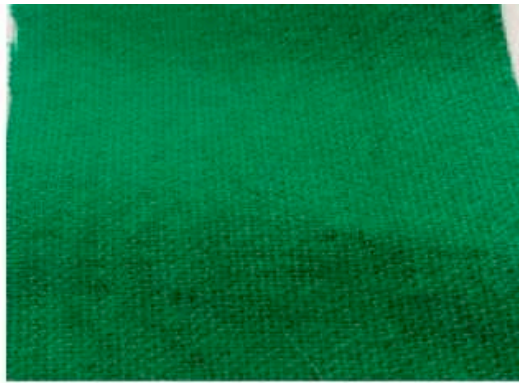


Compeed hydrocolloid plaster

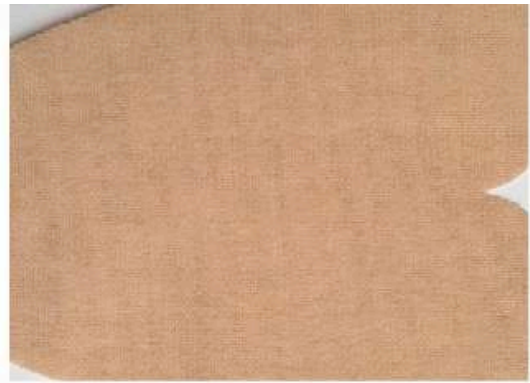
Fig. 6.20: Rubber-like wearable substrate samples (commercially available), images: Prahl (2014)

Rubber-like substrates samples (fig. 6.20) included materials such as visco-elastic polymer gel (Scholl Party Feet), 90% silicone and 10% thermoplastic polyurethane (Undercover Glamour nipple cover), elastomer, polyurethane and hydrocolloid gel (Compeed Callus plaster), Thermoplastic Elastomer Gel (Superdrug bunion protector), soft foam (Scholl Ball of Foot cushion) and natural rubber (unbranded big toe straightener, made in Taiwan). All these materials have a soft touch and skin-like quality, while many of them are washable and reusable.

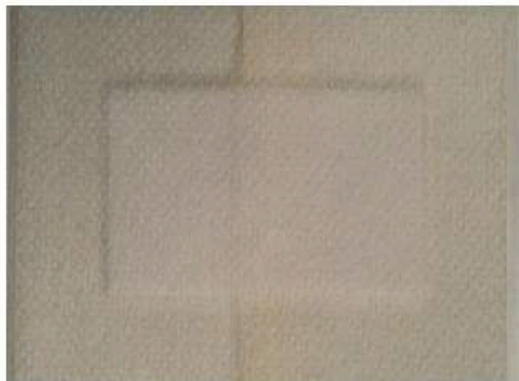
Textile-like



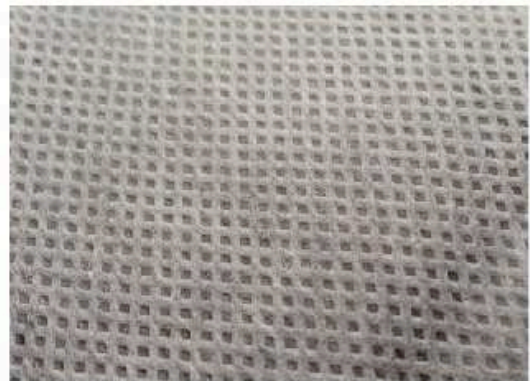
Levotape Kinesiology adhesive tape



Knicker Sticker disposable underwear



Boots adhesive wound dressing



Subtle Butt disposable gas neutralisers



MoYou self adhesive nipple covers



Boots callus relief pads

Fig. 6.21: Textile-like wearable substrate samples (commercially available), images: Prahl (2014)

Textile-like substrate sample materials (fig. 6.21) included knitted cotton and adhesive film (Levotape and knicker stickers), carbon-activated nonwoven (Subtle Butt), polyester and silicone rubber (MoYou nipple covers) and hypoallergenic, medical grade chiropody felt (Boots callus relief pads). Most of the reviewed samples have a soft textured surface, are breathable, due to their proximity to the body or skin and are mostly designed for single use, while some of them are elastic for better movement during activities and can be worn for up to 4 days (Levotape).

Paper and film-like



Prym disposable self-adhesive bra



Frownies facial patches



Wundercover tattoo & skin shields



Prym disposable dress shields



Bare Lifts adhesive breast tape



Elastoplast invisible protection plaster

Fig. 6.22: Paper-like and film-like wearable substrate samples (commercially available), images: Prahl (2014)

Paper-like substrate samples (fig. 6.22) included materials such as 100% polyester with adhesive backing (Prym disposable bra) unbleached natural Kraft paper (Frownies facial patches), synthetic nonwoven with adhesive backing (Wundercover tattoo & skin shields) and polypropylene and polyvinyl chloride (Prym disposable dress shields). Although these samples shared a crisp and paper-like quality, they varied widely in terms of flexibility and surface texture; while some are designed to be breathable and might therefore utilise a perforated or textured surface (Prym disposable bra and dress shields), others are rigid with a low-tech paper feel (Frownies). *Film-like* substrates (fig. 6.22) are mainly utilised for a new generation of transparent plaster products, such as Elastoplast invisible protection plasters, which are made from an ultra-thin elastic polyurethane material and are breathable and waterproof. A similar film-like substrate is used for Bare Lifts adhesive breast lift tapes, which are made from latex-free adhesive film and are hypoallergenic and water resistant.

In addition to the innovative material developments across flexible, plastic and paper electronics (chapter 2), this overview of body-worn and skin-worn material substrates highlighted that some of these commercially available products from the field of health, medical and beauty, could be used as important references for the design of future wearable sensors. While most technological innovations tend to involve new and high-tech manufacturing processes and materials, it will also be relevant to consider innovation opportunities around more low-tech and existing materials, by applying their use in the field of textile-based Wearable Technology.

6.4.2 User workshop 2: Material focus

User-workshop 2 was primarily designed to generate feedback on aspects concerning form (chapter 7), however, it also proved an opportunity to generate insightful responses with regard to user preferences on potential material substrates for wearable sensors. Details regarding the methodology behind this workshop were presented in chapter 4, while operational aspects (such as artefacts created) are covered in chapter 7. This section focuses on the workshop activities and outcomes relevant to the material investigation only. This workshop was held at London College of Fashion on the 6th of February 2014 and was attended by five participants, who were introduced to eight wearable sensor concepts, designed to explore form factors (chapter 7). Each board presented ideas on designs for body-

worn wearable sensors through a collection of images, sketches and some initial mock-ups in combination with a box of a selection of relevant medical, health and beauty samples (section 6.4.1).



Fig. 6.23: Interactive workshop session



Fig. 6.24 Group discussion on materials

As part of an interactive workshop session, each participant spent time studying the concepts in response to a questionnaire (fig. 6.23 and appendix C), which focused specifically on the eight specific on-body locations and particular types of wearables that could be worn in those locations (chapter 7). In addition, this exercise also gave the workshop participants valuable time to touch, handle, wear and test the samples (fig. 6.25) in order to understand and evaluate them in the context of wearable sensor products that can be worn in a variety of locations on the body and skin. In the interest of generating specific feedback on material substrates, this exercise was followed up with a group discussion to exchange and note the participants' thoughts and opinions on preferred material choices (fig. 6.24).



Fig. 6.25: Handling various prototypes and commercially available material samples

During the discussion I noted that in response to the introductory presentation into innovation for wearable sensors, such as tattoo and plaster-like sensors and a wide selection of skin-worn transfer tattoo samples, participants expressed concern about their willingness to wear these types of ‘stick-on’ materials on their skin, as they considered their potentially negative impact on the skin’s ability to move freely.



Fig. 6.26: Preferred choices for body-worn material substrates: Rubberised insoles and bunion protector, Wundercover tattoo paper and Frownies facial patches (all commercially available samples)

Participants were particularly drawn to soft, pleasant to touch materials including the thermoplastic gel used in the soft gel bunion protector and rubberised felt insoles, while they were also positively surprised at the comfort of paper-like products such as the Frownies facial patches and Wundercover tattoo and skin shields (fig. 6.26), which were worn by some participants throughout the duration of the 2 hour event. This opportunity for constructive feedback on both high-tech and low-tech material substrates, provided clarity and inspiration for the final material concepts described in section 6.5 and further informed the design of the wearable sensor collection, presented in chapter 10.

6.4.3 Exploring paper substrates



Fig. 6.27: Cardboard cellulose nonwovens, VTT Finland



Fig. 6.28: Issey Miyake paper fashion

‘Paper and textiles have an exciting and constantly changing relationship. In terms of their structure, qualities and usage, they have many similarities.’
(Leitner, 2005, p. 10)

In her book *Paper Textiles*, Austrian textile artist Christina Leitner highlights the correlation between paper and textiles and is particularly interested in the similarities with regard to the raw materials used, such as plant-based fibres and cellulose; the making process, as she compares nonwoven textile making to paper-making; and the end-use, which shares many applications including interior decoration and personal hygiene products. She argues that in many cases, paper has taken the place of textiles in today’s society, which can be attributed to the fact that paper is often cheaper and more practical and versatile, especially for short-term and disposable usage. Paper and cardboard however, can also be transformed into wearable materials, be it through manufacturing processes or design innovation. In 2013, VTT Technical Research Centre of Finland developed a manufacturing process that can convert recycled paper and cardboard into raw materials for biodegradable nonwovens^{6J} (fig. 6.27), which can be used for products including nappies and sanitary towels, while fashion designers have long been interested in creating fashion with paper and paper-like textiles. The fashionability of paper as a textile was further demonstrated at the ‘Paper Fashion’ exhibition at the Mode Museum in Antwerp^{6K} in 2009, which showcased artefacts by many designers including Hussein Chalayan, John Galiano and Issey Miyake (fig. 6.28), and moved on to the Design Museum in London later in the same year.

With regard to wearable sensors and printed electronics, the potential of paper-like substrates was documented in chapter 2, while the wearable substrates overview earlier in this chapter presented compelling low-cost paper-like substrates utilised for body-worn products, such as disposable bras and facial patches. Furthermore, the user workshop highlighted a positive response to paper-like adhesive, body-worn products, and I therefore decided that I needed to delve deeper into the creative opportunities around paper-like textiles and materials.

Papermaking

In order to understand and explore the potential of paper, I undertook a papermaking short-course at Morley College in London. This course enabled me to create my own paper samples, utilising the specific raw materials I wanted to investigate prior to designing the final collection of artefacts. I already had some rough ideas in mind for suitable themes, stories and aesthetics and this phase of learning, designing and making of paper samples, gave me an early opportunity to firm up and test some of these ideas in practice.



Fig. 6.29: Denim inclusions and indigo dyed cotton rag pulp during papermaking process, Prael (2014)

One of the themes I was contemplating for a fashion-inspired collection was the integration of denim, both in terms of colour and texture, as denim jeans and jackets are generally considered to be wearable in combination with many types of other clothing and by a large section of the population, making the concept of denim-inspired wearable sensors an interesting prospect. I therefore experimented with a variety of approaches to bring a denim look, feel and touch to paper samples and this included utilising recycled denim rag pulp, indigo dyeing white cotton rag pulp and integrating recycled denim fibre inclusions into the paper during the sheet-forming process (fig. 6.29).



Fig. 6.30: Recycled magazines, cotton rag pulp and denim inclusion paper samples, Prah (2014)

I also experimented with the concept of recycling, and in particular recycling of seasonal fashion magazines. Paper used for magazines tends to be very flimsy and would not make a solid pulp for paper and paper-based products by itself, so I utilised white and denim coloured cotton rag pulp with denim fibre inclusions and added shredded fashion magazines to create subtly different shades of denim paper, while adding specks of highlight colour (fig. 6.30).



Fig. 6.31: Thermochromic pigment dyed and painted cotton rag pulp and natural fibre inclusion paper, Prah (2014)

I also tested the concept of stimuli-responsive paper, in the context of designing low-tech wearable sensors that could provide instant visual feedback to the wearer (chapter 2). I therefore chose to work with thermochromic pigments, which in combination with Permaset Aqua eco-friendly ink ^{6L} were used to dye white cotton rag pulp into strong shades of pink and blue. Although the dyeing process produced beautiful and strong colours the thermochromic effect did not appear to work on the

paper samples I produced with this method. However, I also made samples where the thermochromic pigments were painted onto the wet sheets of paper and this time the effect was visible and the colour disappeared when heat was applied to the paper (fig. 6.31).

Another approach to create stimuli-responsive paper-based wearable sensors was the use of natural red cabbage dye, which can be utilised to create pH indicators. White cotton rag pulp was dyed with red cabbage juice and, once dry, created a vibrant shade of purple (fig. 6.32). As discussed in chapter 2, this concept could be a mechanism to measure environmental data, such as the acidity of rain, while there may be also be potential in measuring the acidity levels of the wearer's sweat or skin.

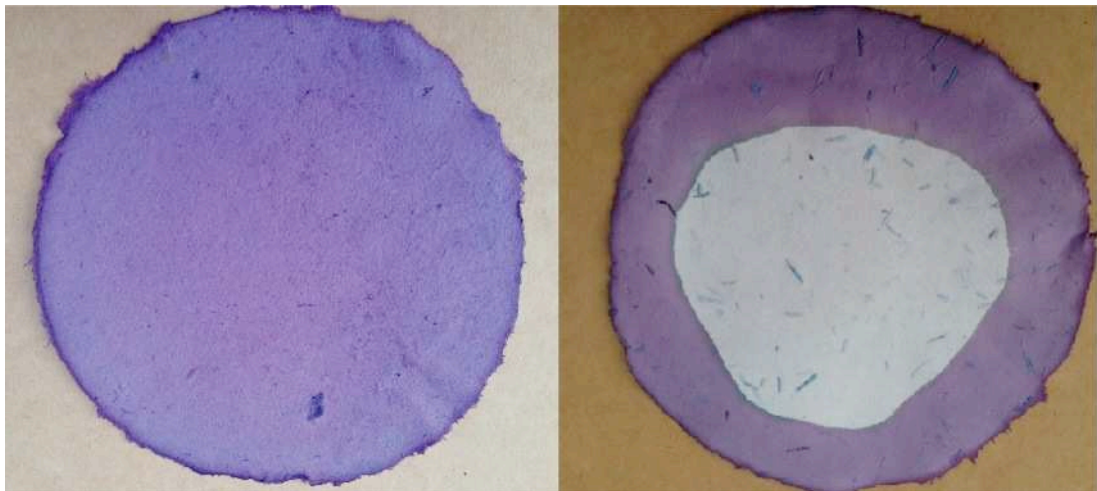


Fig. 6.32: Red cabbage dyed cotton rag pulp and cabbage dipped cotton rag pulp and denim inclusion paper, Prah (2014)

The final idea around paper substrates was the concept of embossing, as this could add decorative aesthetic and tactile aspects to paper-based wearable sensors. Various paper sheets were formed with the use of plastic and felt stencils, which added permanently formed surface interest to the samples during the drying process (fig. 6.33). This intense phase of papermaking proved to be especially inspiring in view of the later stages of the design process, as these initial ideas were further developed into concepts for two of the final wearable sensor collections (chapter 10).

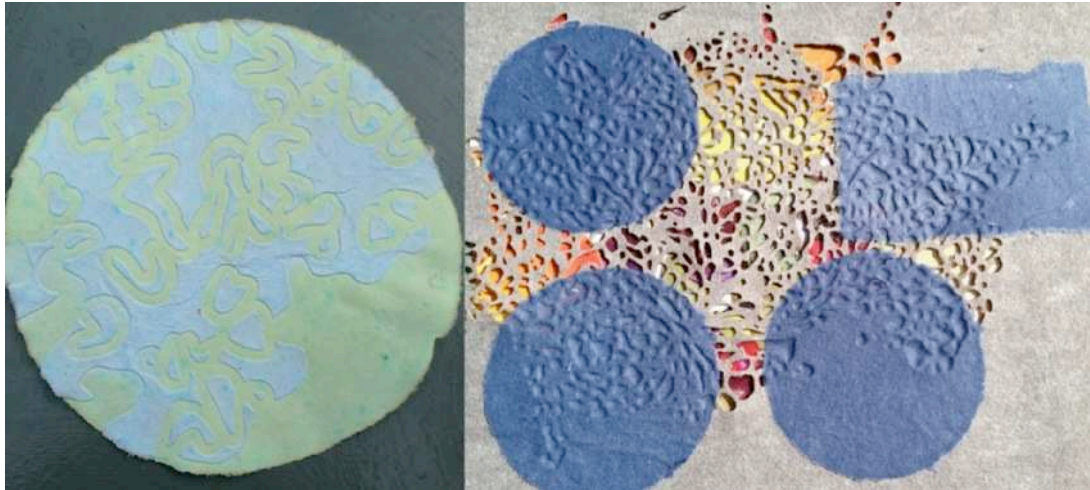


Fig. 6.33: Embossed thermochromic paper and wet denim coloured paper drying on stencil, Prah (2014)

Wear testing

Beyond designing and making paper-based substrate samples, I also needed to think about if and how some of these high and low-tech substrates (such as the 100% polyester disposable bra and synthetic nonwoven tattoo cover stickers and Frownies facial patches) would perform when worn directly on the skin and how they might be affected during specific conditions and activities, such as high temperatures and participation in exercise and sport. I therefore undertook some basic wear testing of a selection of the commercially available paper-based substrates reviewed earlier in this chapter.



Fig. 6.34: Disposable bra material worn on forearm for 24 hours

The adhesive 100% polyester disposable bra material was tested on the inner forearm (fig. 6.34) and due to the fact that it was so comfortable to wear, I forgot to take it off after 6 hours, which is the maximum recommended wear time. This resulted in difficulties when pulling off the adhesive substrate and it caused slight skin irritation. However, as wearable sensors would not need to be worn for such extensive periods of time to generate the required data from the wearer, this type

of material could make an excellent potential substrate and performed well even during a 75-minute strenuous yoga class, due to its breathability enabled by the perforated surface pattern.



Fig. 6.35: Synthetic tattoo cover material worn on forearm for 24 hours

Likewise, the synthetic nonwoven adhesive tattoo cover was wear-tested on the inner forearm for a 24-hour period (fig. 6.35), and was also comfortable to wear, while it blended in perfectly with the skin, due to its skin-like colour and camouflage pattern. My skin was slightly irritated after the patch was removed, however, this is unlikely to occur after a more suitable and shorter wear-time.



Fig. 6.36: Frownies Kraft paper-based facial patches with thermochromic print

Examining the Kraft paper material further, I tested the idea of adding a responsive print motif to the substrate utilising thermochromic ink, which would respond to the user's body temperature. As it was a particularly hot time of the year, the colour faded almost immediately as the substrate came in touch with the warm skin (fig. 6.36). This colour change was even more prominent during exercise, as the colour stayed a very light shade of the pink print, throughout the 75-minute dynamic yoga class (fig. 6.37).



Fig. 6.37: Perforated Frownies Kraft paper-based patches worn on forearm for 3 hours

For the sample worn during exercise, I added perforation to the substrate to ensure breathability, inspired by the design of the disposable, adhesive bra, as shown in section 6.4.1. However, this sample started to peel off the skin around the edges after less than an hour during dynamic yoga class, peeled off further around the edges and in the middle and eventually came off completely after 3 hours (fig. 6.37). This was either due to the hot air temperature and wear during exercise, or the fact that the added perforation affected the material's ability to adhere to the skin properly.

6.5 Nonwoven materials: Rubber-like, paper-like and felt-like

“Nonwovens are a growing sector within industry, providing economical and often environmentally advantageous alternatives to conventional textile materials...their engineering ability, adaptability and economical and environmental viability make them important fabrics to consider in the development of smart clothes and wearable technologies.” (Kane, 2009)

Loughborough University textiles researcher and lecturer, Faith Kane's quote (2009, p. 179), highlights the great potential nonwoven materials and textiles show to contribute to material innovation in the Wearable Technology sector, and based on the design opportunities for cost-effective, easy to use and potentially recyclable and biodegradable materials, nonwovens were chosen as the particular focus of this research. This decision, although backed up by the understanding that nonwovens are one of the fastest growing sectors of the textile industry (Chapman, 2010), is based on the encouraging outcomes of the design and making of the material stories and further material research and sampling, presented earlier in this chapter.

Although definitions on what classifies as a nonwoven vary, these types of materials can be broadly described as ‘*a sheet material made from fibres or filaments that is strengthened by bonding using one or more of several techniques*’ (Chapman, 2010, p. xvii). Nonwovens do not utilise knitting or weaving procedures to convert fibres and yarns into materials and textiles and have an extensive range of consumer, medical and industrial applications, which comprise durable as well as disposable products, subject to the raw materials utilised to create the nonwoven. A wide range of synthetic and natural fibre types can be utilised to manufacture nonwoven products, although man-made fibres, such as polypropylene and polyester, dominate in nonwovens production. Due to the nature of the nonwoven process, post-industrial and post-consumer reclaimed and recycled fibres have long played an important role in the manufacture of nonwoven materials. With regard to end-of-life considerations, biodegradable fibres such as cotton, Tencel and Polylactide (PLA) biopolymers are becoming more relevant in the industry, while research and innovation further focuses on the development of recycling processes and machinery for nonwoven manufacturing and post-consumer waste.

Within the context of this research, I take an even broader view on what constitutes a nonwoven material or textile, as the material concept embraces any materials or textiles not manufactured through knitting or weaving, while the focus is firmly on the development of nonwoven materials and textiles, that are either biodegradable or recyclable as part of a closed-loop design strategy. Academic researcher and practitioner Kate Goldsworthy (2010) suggests that, based on the understanding of Cradle to Cradle or closed-loop principles, textile designers can choose to work with either *natural* or *synthetic* materials, and it is this very categorisation that informed the next steps of the material exploration, further providing the opportunity to investigate wearable sensor lifespan in line with durability, recyclability and biodegradability, proposing *disposable* as well as *reusable* wearable sensor concepts.

Of particular interest is the question what a *wearable material* could constitute in the context of textile-based wearable sensors, as our understanding of textiles continues to evolve. Textiles are generally defined as a type of cloth, which consists of a network of fibres, thread or yarn, created through weave, knit, crochet, lace or nonwoven manufacturing techniques, while author and textiles lecturer Miller (1992) further elaborated that textiles are made from fibres, which can be converted in to a yarn first, or the fibres can be converted directly into the cloth.

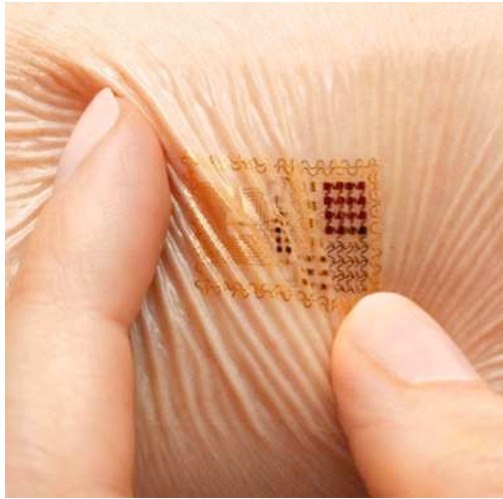


Fig. 6.38: MC10 flexible epidermal electronics Fig. 6.39: Fabrican sprayable nonwoven fabric

By extending my focus from the traditional understanding of what comprises a textile, to considering the more divergent concept of ‘wearable materials’, this research explores the potential of more unconventional types of nonwoven materials and textiles, inspired by, and building on, innovation from non-technical as well as technical fields. These include emerging material technologies based on epidermal and electronic tattoos (fig. 6.38), as presented in chapter 2 and the design and making of nonwoven textiles, which can be formed and shaped around the contours of the body, such as Gary Cass and Donna Franklin’s Micro‘be’ Fermented Fashion^{6M} and Fabrican’s^{6N} sprayable fabric (fig. 6.39).

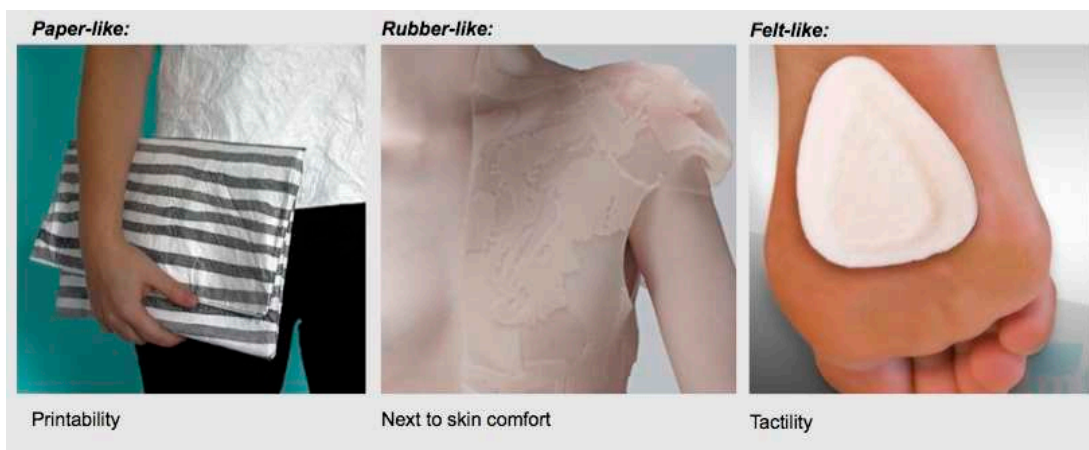


Fig. 6.40: Paper-like, rubber-like and felt-like wearable material concept, utilising secondary images, Prahla (2014). (a) Tyvek clutch by Design & Paper, (b) ‘Inlaid Skin’ by Andreea Mandrescu and (c) felt metatarsal pad.

Following the outcomes of the various sampling and research activities, I defined three nonwoven substrate categories (fig. 6.41), which were to be the focus for the final design stage:

- *Rubber-like* materials, as they can provide excellent next-to-skin comfort and functionality;
- *Felt-like* materials, as they offer tactility and comfort, an essential feature for successful user interaction;
- *Paper-like* materials, as they can be printed with the necessary enabling technologies easily and cost-effectively

All three categories further offer excellent opportunities to embed and provide end-of-life solutions, thus creating both recyclable and biodegradable products, while rubber-like and felt-like sensors could also be designed to be more durable in order to be reusable, before they can be recycled or composted at the end of their life.

6.6 Conclusion



Fig. 6.41: Developed 'material' outcome and focus, Prah (2015)

At the beginning of the practice-based 'material' investigation, I asked the question whether a closed-loop approach to material substrate design could inspire new concepts for wearable sensors and it is apparent that the framework of closed-loop design principles served as an inspiring method to initiate and generate a diverse assortment of qualitative data including artefacts, with the particular focus of producing initial themes and ideas for the eventual design of the wearable sensor concepts. Indeed, my design practice and subsequent evaluation of these outcomes led to the development of a more focused investigation into nonwoven substrates, while further categorising these into rubber-like, felt-like and paper-like synthetic and natural material substrates, due to their diverse and appropriate features (including

next-to-skin comfort, tactility, printability, cost-efficiency and recyclability or biodegradability).

This material investigation employed various practice-based methods to generate a diversified range of data in order to merge with the outcomes from the form and function investigations (chapters 8 and 9), to inform the design brief (chapter 9) and inspire the subsequent design and development of the wearable sensor collections (chapter 10). These methods included: a) the creation and evaluation of material concepts, which included visual boards and material swatches, b) a wearable substrate overview, which presented a diverse range of commercially available and cheap samples, c) a user workshop, which produced insightful feedback on wearable material preferences, and d) an additional phase of material sampling, focusing on paper making and wear testing. The combined use of these methods ensured that the data was varied, thus offering a more objective and detailed narrative for further development. This approach further provides a wide range of design outcomes (i.e. boards, swatches, systematic materials overview, user feedback and wear-testing), which can be used by other designers and researchers, as a foundation or inspiration to their own work.

In addition, the preparation of my peer-reviewed conference paper 'Wearable Sensing for Preventative Health: A material-driven design exploration' (Prah, 2014a), presented at the Transition: Re-thinking Textiles and Surfaces Conference at the University of Huddersfield, facilitated in-depth reflection on this material investigation and contributed significantly to planning and writing this chapter.

Chapter 7: Exploring form factors for wearable sensors

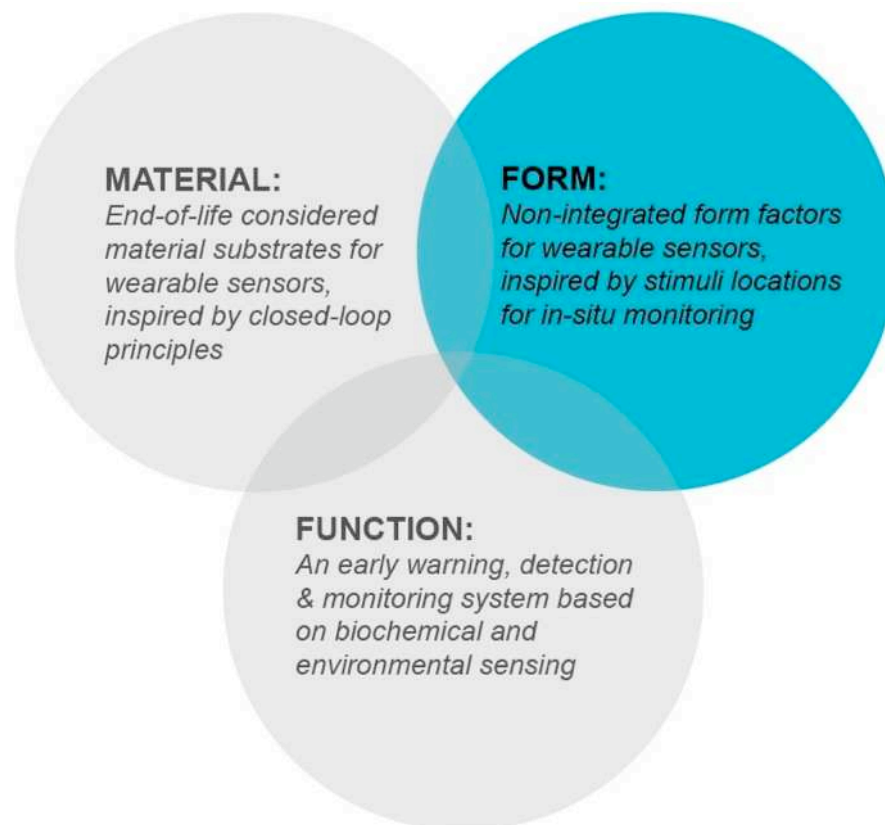


Fig. 7.1: Diagram showing FORM focus as part of three-stranded investigation, PrahI (2015)

Chapter 3 highlighted design opportunities for wearable sensors that can act as an early warning, detection and monitoring system based on biochemical and environmental stimuli and proposed the particular focus on non-integrated types of wearable sensors, in order to offer alternatives to permanently and seamlessly integrated sensors in clothing. Therefore, the aim of this strand of investigation was to formulate a suitable approach for the design of shapes and styles for wearable sensors, which addressed the need for in-situ VOC and EMR sensing from the wearer and the environment, while considering their placement and use in particular locations on the body.

The notion of non-integrated wearable sensors could contribute new possibilities for providing more affordable, accessible and easy to wear on-body monitoring, thus giving a greater number of potential users the opportunity to take active control of their health as part of a preventative lifestyle. A considerable advantage for this approach is that wearable sensing devices could integrate more easily into the users' existing routines, as they could be worn either visible or concealed to others,

subject to the chosen stimuli location on the body, and therefore give the wearer more freedom of choice.

“The body is a useful design as it has a useful number of places to put things whether smart clothing or wearable technology...Even so there are only so many places [we] can attach things to the body, without piercing or creating extra pockets. “ (Bryson, 2007, p. 5)



Fig. 7.2: On-body activity tracker positions



Fig. 7.3: Face-worn Wearable Technology

Indeed, as Bryson (2007), academic researcher and educator at the University of Derby, points out in his paper ‘Unwearables’; there are many on-body locations where Wearable Technology devices could be placed, as *‘new wearable form factors are evolving at an incredible rate’* (Mautone, 2014). We can already recognise that our feet (i.e. shoes and insoles), wrists (i.e. activity trackers, smart watches, smart jewellery, fig. 7.2), hands (i.e. gloves and rings), waists (activity trackers and belts, fig. 7.2), heads (i.e. headsets and headbands) faces (i.e. smart glasses and goggles, fig. 7.3), ears (i.e. ear buds) and even eyes (i.e. contact lenses) have become much coveted body parts for designers and manufacturers of Wearable Technology devices, clothing and accessories.

Preliminary testing of wearable devices

Wearability could have a diverse range of personal meanings for different users but can generally be defined as something that is suitable for being worn and terms often associated with wearability are comfort, practicality and durability. In particular view to Wearable Technology, researcher at Carnegie Mellon University, Pittsburgh,

and colleagues, Gemperle *et al.* (1998, p.116), stated that '*Wearability is defined as the interaction between the human body and the wearable object*', while Dunne (2010) asserted that the key to designing sensor-enabled clothing is the right balance between sensor placement (the optimal placement of the technology in order to perform accurately) and the placement of the technology on the user's body, with regards to their comfort and wearability.

As a starting point to this exploration of form and in order to gain insights into potential issues around the 'wearability' of existing Wearable Technology devices, I carried out some simple wear testing with two types of devices. These devices fall into the hardware category and this preliminary phase of wear testing combined observations on the experience of wearing and using the two devices, considering their shape and form in relation to being worn or carried on the body, in combination with aesthetic and practical aspects. As an initial element of an intense phase of PAR (chapter 8), I tested a Fitbit One activity tracker and Apple iPhone 5, and the particular findings relevant to the exploration of form design, are described further on in this section. The Fitbit One activity tracker tracks steps, distance, stairs climbed and calories burnt and monitors sleep quality and can be connected to laptops, tablets and smart phones via wireless syncing. In order to function correctly, the device needs to be worn in a pocket, or clipped onto a belt, waistband, bra or top for activity tracking (fig. 7.4), while it inserts into a wristband, which is supplied with the purchased device, to monitor sleep.



Fig. 7.4: Initial wear testing of a Fitbit One activity tracker

Fitbit One was worn every day, all day, for a period of three weeks, as it is designed to track general activities such as walking and climbing stairs, as well as particular sports and fitness activities, in order to inform the wearer whether their daily goal has been achieved. During the testing period, specific activities included two runs and three dynamic yoga classes per week, during which the device was either clipped onto the waistband of my yoga pants or running tights, or the neckline of a sports bra.

My observations during the testing period (focus on wearability) included the following:

- *Purchase:* I was frustrated with the lack of choice/ customisation at point of purchase, as the only option was to select between two colourways (black and burgundy)
- *General wear:* It proved difficult to remember to wear the item on a daily basis, especially when changing outfits during the day
- *Sports specific wear:* I found the required wear locations did not always suit my sporting activities, as the device position was problematic during a variety of yoga poses (i.e. lying on the front of the body), in addition the need to clip the device in a particular position on the sports bra caused potential for wear and tear around the stitched and sometimes elastic neckline of the garment
- *Other:* I would have preferred to use the Fitbit One's wristband at times, however this location is only suitable for monitoring sleep, which was not tested

In addition it transpired that Fitbit One's limited parameters proved frustrating (chapter 3); it can accurately track walking and running but not activities such as yoga, weight lifting or cycling. This issue is directly linked to the particular type of enabling technology used, which also dictates the specific and restricted wear locations. This point reiterates that a technical device's form and function are inherently linked together. Therefore it is essential to explore the design and development of form factors for wearable sensors, with the device's functionality, user needs and requirements during potential use-situations, in mind.

The second wear testing phase involved the iPhone 5, and although I carry my phone with me on a daily basis anyway, specific testing constituted a period of three

weeks, when I utilised the phone as a monitoring device for twice-weekly runs. The device's functions were enhanced through the addition of various apps, including pollution, heart rate and mood monitors (chapter 8).



Fig. 7.5: Initial wear testing of an iPhone 5 during running; (a) iPhone sleeve, (b) iPhone sleeve in-situ with phone, (c) iPhone in pocket of top, (d) iPhone in waterproof bag inside pocket

My observations during the testing period included the following:

- *Comfort:* The Nike forearm sleeve phone carrier I had purchased for the purpose of making my iPhone wearable, proved to be a poor choice; although the phone fitted into the sleeve nicely without it being worn, once it had to fit around the contours of the arm, there was not enough room to allow comfortable wear or operation (fig. 7.5 a and b)

- *Security*: I felt uncomfortable running with an expensive device strapped to my arm, visible to anyone around me in the park or the streets
- *Operation*: As an alternative I carried the phone in a zip pocket on my running top (fig. 7.5 c), this meant that it was very difficult to operate the phone during the activity of running and it rubbed against my body as I ran
- *Other*: Weather proved to be a concern as the phone had to be wrapped in a sandwich bag (inside my top) to protect it from the rain (fig. 7.5 d)

This period of wear testing was by no means intended as a systematic exercise but designed to lay the foundations for the subsequent investigation into form, through experiencing some of the issues with regards to wearability of sensing and monitoring devices at first hand. It also contributed to my determination to develop a relevant approach to the design of in-situ sensing and monitoring devices, and the process and outcomes are presented in the remainder of this chapter.

7.1 Design for in-situ sensing & monitoring

It is significant to note that this project focuses on the design of concepts for the near to mid-term future, which is likely to see an unprecedented growth in wearable sensing devices and consequently increase user acceptability of such products and systems, although more advanced concepts for sensing for health and wellbeing, such as ingestible ^{7A} or implantable ^{7B} sensing technologies, are already on the horizon. Despite these innovative developments for niche markets and early adopters, mainstream adoption of such futuristic wearable sensors is likely to take time and while this research acknowledges such future opportunities, it concentrates on the design and development of sensing devices that can be worn by the user on the *outside* of their body. The investigation further focuses on the particular aspect of designing 'in-situ' wearable sensor concepts, which require the sensor to be in contact with whatever stimuli they are sensing and remain in their optimal position during wear. Therefore the shape and design of the wearable sensors should be informed and determined by the actual location of the stimuli to be detected in order to provide suitable form factors, as these devices will be worn as part of an existing day-to-day lifestyle and managed by the user, rather than being used as part of a medical examination in a hospital or surgery situation.

The project focuses on biochemical sensing, with a particular focus on VOCs emitted from the wearer, and environmental sensing of VOCs detected in indoor and outdoor ambient air, as well as potentially harmful EMR emitted from a variety of sources including power lines, wireless transmitters, TVs, computers and laptops and personal devices such as smart phones and tablets (chapter 3). Considering the multitude of locations on and around the body where human and environmental VOCs and EMR could be monitored, there are many untapped on-body positions where sensors could be worn or attached and this element of the research therefore asks:

- Can design in response to VOC and EMR stimuli locations inspire new types, shapes and styles of wearable sensors in the context of Preventative Health?

7.1.1 Stimuli locations as design inspiration

The term stimuli location is used to describe precise or general positions, where the VOCs may occur on the wearer of a wearable sensing device or where VOCs and EMR may be present in their environment. It is first important to investigate where these internal and external stimuli can occur, in order to consider how their location could inform or determine the design of wearable sensors.

Internal stimuli

In the case of internal VOCs, this is more clear-cut, as they are emitted in breath and various body fluids and this research focuses on designing biochemical sensing applications, based on biomarkers emitted from the skin. Internal VOCs and other biomarkers can derive from eccrine, sebaceous and apocrine sweat glands, which are located all over the body but are most concentrated on the forehead, upper back, neck, lower back, forearms, underarms, palms and feet (fig. 7.6), and designing wearable sensing devices aimed at these specific on-body locations therefore makes for an compelling prospect.

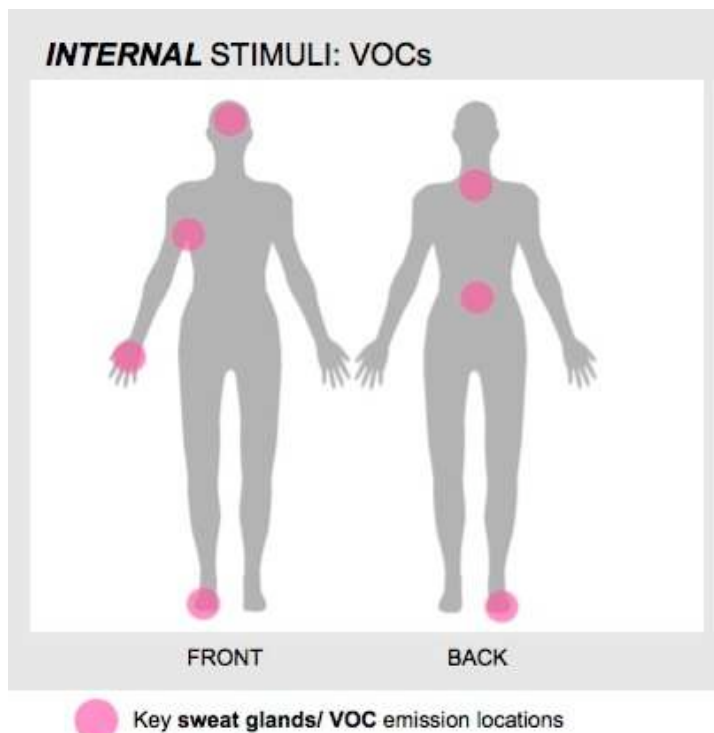


Fig. 7.6: Internal stimuli location diagram, Prahl (2013)

Emerging research and innovation into sweat sensing devices is very much focused on plasters or tattoo-like patches, which can be worn in many different locations on the body, applied directly to the skin (chapter 2). While this means that the wearable sensor can be placed in any of the key locations as outlined above, such as near the wearer's armpit ^{7C} (fig. 7.7), or on the forearm ^{7D} (fig. 7.8), some users may not be comfortable with wearing such a device on their skin. However, as these types of sensors are very versatile, they provide the potential to easily integrate into the wearer's existing lifestyle, either in a visible or concealed manner, subject to the wearer's preferences.

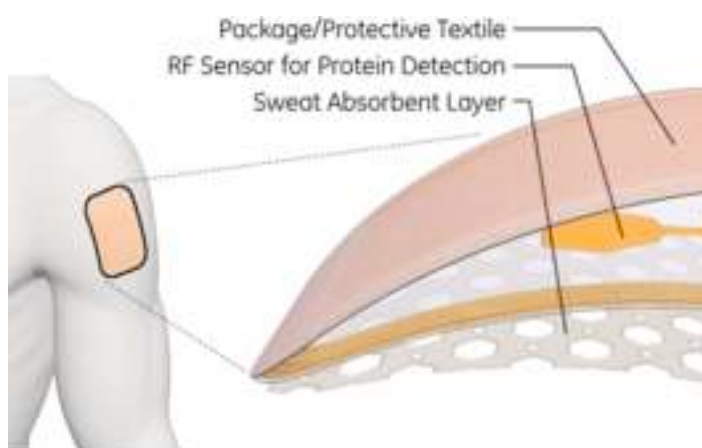


Fig. 7.7: Sweat sensing plaster (GE Global Research)



Fig. 7.8: Printed sensor (UCSD)

A commonly used approach in previous academic research in this field, is to integrate standard sensors and sensing elements that are made wearable by attaching them to items such as waistbands and belts, in order to monitor sweat on the lower back (fig. 7.9) or other locations on the body. Coyle *et al.* (2009) demonstrated and described wearable textile sensors that can measure sweat pH and provide real-time information during exercise on sweat activity. The sweat sensor was integrated into a textile waistband, which was worn during exercise (fig. 7.9), and the researchers believe that these kinds of sensors could provide valuable information for athletes in regard to their rehydration needs and other physiological data, thus offering opportunities for applications in both sports performance as well as healthcare. These experimental types of sensors are not designed for everyday use, and for the purpose of this research, are therefore not considered as inspiration for the design of new form factors. However, they do provide important background information in terms of potential requirements such as comfort and functionality.

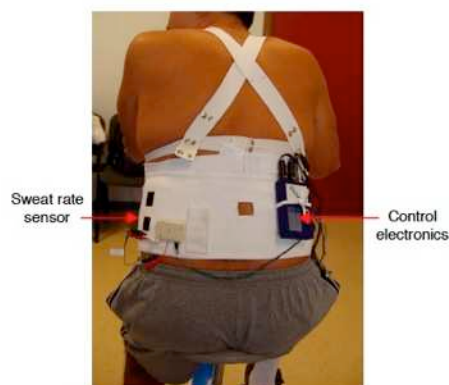


Figure 4. Experimental set-up, sweat rates sensor is positioned on the left, the pH textile patch on the right behind the control unit

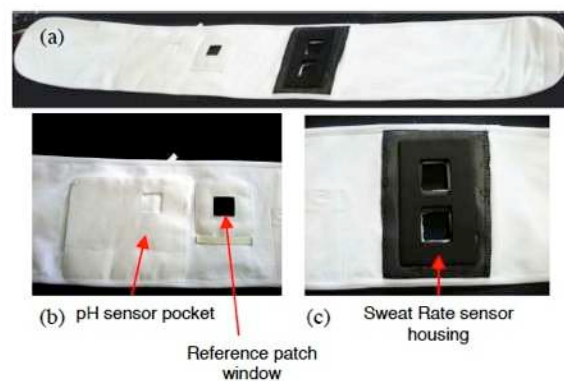


Figure 3. a) the waistband b-c) details of the housings of the pH sensing patch and sweat rate sensor

Fig. 7.9: Experimental textile sensors to measure sweat pH, Coyle *et al.* (2009)

External stimuli

In contrast to the detection and monitoring of internal stimuli from specific locations on the wearer's body, locations for external stimuli are much harder to determine, as they occur in the ambient air. Furthermore this project considers two different types of external stimuli, VOCs and EMR, which may occur in diverse locations near and around the body, as indicated by the external stimuli location diagram (fig. 7.10).

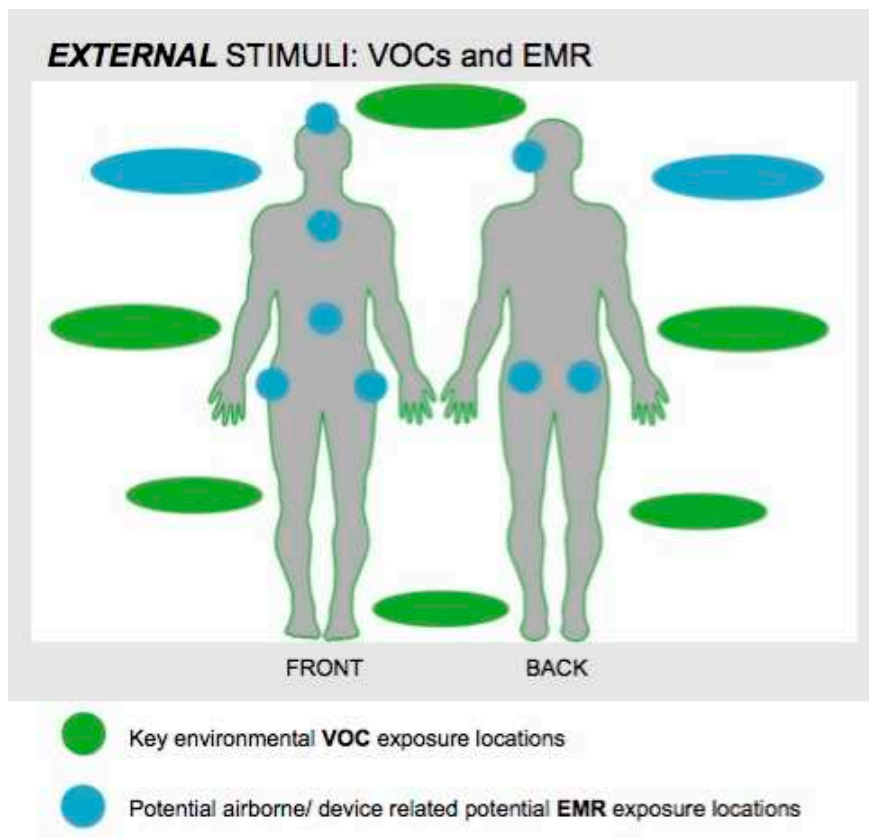


Fig. 7.10: External stimuli location diagram, PrahI (2013)

The major routes for human exposure to pollution and chemicals are through inhalation, skin or ingestion. Environmental VOC measurements can be utilised to sense harmful indoor and outdoor pollution and this suggests that wearable sensors could potentially be placed around the head and face area as well as anywhere on the (exposed) skin. The research therefore focuses on exploring wearable sensor placement in those areas, further considering the lower leg area as a potential position, as pollution detected low to the ground may provide alternative readings to sensors placed in the head/ face area and stationary monitoring stations in the environment, which are generally positioned above head level.

Scientific research into the impacts of exposure to EMR is still relatively limited (chapter 3), and it is therefore difficult to identify exact key routes for potentially harmful human exposure. However, for the purpose of this project, exposure could be divided into two key sources: a) electromagnetic rays emitted from power lines, wireless transmitters, microwaves and TVs into the user's ambient environment and b) exposure from handheld and 'on-body' electronic devices such as mobile phones, laptops and tablets. Mobile phones are often kept in pockets inside the wearer's clothing and when in use, are handheld near the head and ears (fig. 7.10), while

laptops and desktop computers could potentially expose the user to dangerous radiation in the face, chest, stomach, groin and upper leg area. However, as the potential health impact of using of mobile phones is currently causing the most concern, one of the key locations for the creative investigation was selected as the head/ face area.



Fig. 7.11: Clarity wearable air pollution sensor



Fig. 7.12: Estimote Nearable sensor

As concerns about the negative health impacts of pollution are growing worldwide, we have been able to witness a wealth of research projects and new product developments and services addressing the need for pollution detection and monitoring. It is important to note, that, with regards to form design, most of these are either hand-carried (such as sensors attached to or integrated into mobile phones) or are designed to be wearable in a variety of positions near or on the body. Recent examples include the WEPA box, a wearable air pollution sensor ^{7E}, which attaches to the wearer's belt to measure ambient air quality and Clarity ^{7F}, a keychain-sized wearable air pollution sensor, that clips onto clothing, accessories or bicycles (fig. 7.11). Another interesting concept is the Estimote Nearable ^{7G} sensor system (fig. 7.12), which utilises small adhesive stickers that can be attached to any ordinary object, in order to provide sensing ability and digital connection to smart devices. Considering the potential multitude of locations suitable for monitoring ambient air and surroundings for VOCs and EMR and the lack of scientific evidence of preferred on-body locations for EMR detection, the concept of adhesive and movable sensors may be more adequate than sensors designed with specific on-body positions in mind.

7.1.2 Designing with on-body locations in mind

While the design of initial exploratory prototypes (chapter 5) only considered the palms and inner forearms as stimuli locations, this subsequent stage of design research takes a more systematic approach by looking at a greater selection of potential on-body locations for wearable sensors. Merging the considerations for both internal and external sensing as described above, the focus is on investigating the following eight on-body locations: head, face (including forehead), back & neck, underarms, forearms (including wrists), hands (including palms), legs and feet. The first step of this investigation included an overview of a selection of commercially available non-technical types of wearable products, including fashion, sports, beauty and medical applications, based on the identification of the key locations outlined above. Reference images available on the Internet (such as blogs and commercial websites) were arranged in a systematic manner and this simple but essential procedure to evaluate existing form factors, contributed greatly to inspiring the design and development of the initial concepts (section 7.2.1) and final design concepts (chapter 10).

On-body locations: Internal stimuli

Reference images and samples reviewed to inform the design of wearable sensing devices for *internal* stimuli from the wearer comprised back & neck, underarm, forearm, hand and foot-worn examples. *Back* and *neck-worn* examples (fig. 7.13) consist of accessories such as snoods, medical neck therapy wraps and posture braces and adhesive medical sports tapes, which can be applied in specified configurations to support particular parts of the back, while *underarm-worn* accessories (fig. 7.14) of interest include adhesive and elastic strap armpit sweat pads, arm sleeve compression garments and shoulder brace supports.

Back & neck



Fig. 7.13: Reference images (Internet) for neck and back-worn accessories: (a) snood, (b) collar therapy wrap, (c) Kinesio pre-cut muscle tape and (d) posture control brace

Underarms



Fig. 7.14: Reference images (Internet) for underarm-worn accessories: (a) underarm sweat pads, (b) compression sleeve garment, (c) underarm sweat pads, (d) shoulder brace

Accessories worn on the *forearms* (fig. 7.15) include various types of arm sleeves for sports and fashion use, wrist warmers and jewellery cuffs and *hand-worn* accessories (fig. 7.16) include adhesive decorative false nails and wraps, fingerless gloves, gloves and textile-based jewellery.

Forearms

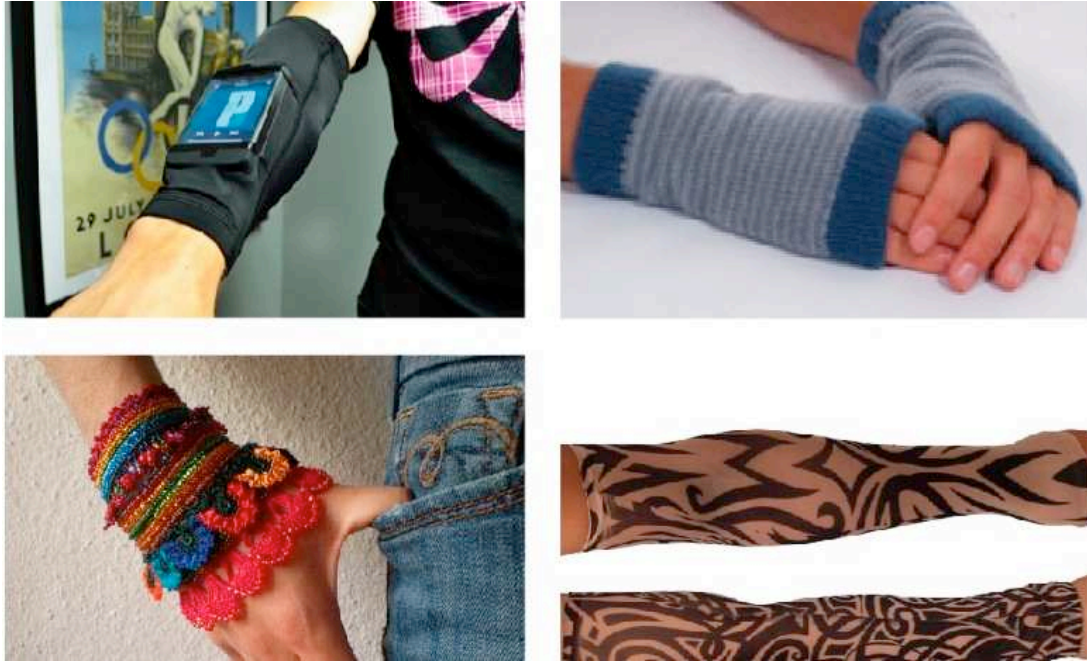


Fig. 7.15: Reference images (Internet) for forearm and forearm-worn accessories: (a) phone sleeve, (b) wrist warmers, (c) beaded crochet cuff (d) printed tattoo sleeves

Hands



Fig. 7.16: Reference images (Internet) and sample image for hand-worn accessories: (a) nail wraps, (b) photo of fingerless glove sample, (c) fingerless gloves, (d) crochet ring set

Feet



Fig. 7.17: Reference images (Internet) and samples for foot-worn accessories: (a) latex bunion protector, (b) latex swim sock, (c) photograph of crochet/ padded foot accessory and (d) photograph of insole samples

Relevant *foot-worn* examples (fig. 7.17) consist of products such as medical bunion protectors, latex swim socks, decorative foot accessories and insoles.

On-body locations: External stimuli

Reference images and commercially available samples reviewed to inform the design of wearable sensing devices for *external* stimuli, including harmful ambient air pollution as well as ambient and device specific EMR, comprised head, face and leg-worn examples. *Head-worn* accessories (fig. 7.18) include headbands, hats, caps and ear warmers and *face-worn* accessories (fig. 7.19) such as adhesive under-eye and forehead beauty patches, face-slimming masks and protective pollution masks, while *leg-worn* accessories (fig. 7.20) included athletic leg and calf compression sleeves and legwarmers.

Head



Fig. 7.18: Reference images (Internet) for head-worn accessories: (a) swimming cap, (b) headband, (c) ear warmers and (d) hat

Face



Fig. 7.19: Reference images (Internet) for face-worn accessories: (a) facial patches, (b) BioBliss forehead patch, (c) slimming face mask and (d) pollution mask

Legs



Fig. 7.20: Reference images (Internet) for leg-worn accessories: (a) calf support, (b) compression sleeve and (c) leg warmers

Adhesive

Most of the examples reviewed were designed to be worn on specific body parts, and therefore consider the particular body part's form as part of the design process. However, it is also relevant to observe that products such as sports support tape is either provided as a standard adhesive tape, which is offered on a roll for the user to cut to the desired shape, or pre-cut and packed in a particular configuration (fig. 7.13 c) to fit and support specific body parts.

Beyond the eight selected on-body locations, it is also relevant to establish that adhesive products aimed at particular body parts, can be applied in two ways; they are either worn directly on the skin, such as disposable adhesive bras (fig. 7.21 c) and sports tape (fig. 7.21 a), or can be attached onto or into items of clothing, such as underwear (fig. 7.21 b), to be near a particular location on the body. Other wearable accessories that make use of existing clothing or footwear as a 'carrier' include medical insoles and patches, which are worn inside shoes (fig. 7.17 d).



Fig. 7.21: Reference images and samples for adhesive accessories: (a) photograph of Kinesio sports tape pack, (b) adhesive gas neutralisers and (c) adhesive strapless bra

7.2 Form factor design concepts

The simple overview of this broad selection of non-technical and commercially available wearable products played a critical part in inspiring the next and more refined stage of the practical investigation, which included the creation of eight initial concepts, developed to explore and test possibilities around designing non-integrated wearable sensing devices with particular on-body locations in mind. In line with the opportunities concerning design for Preventative Health presented in chapter 3, the concepts are intended to be worn as part of a regular routine and therefore need to integrate easily into the user's existing lifestyles, activities and outfits, in order to enable participation in a preventative lifestyle through the use of biochemical and environmental sensing.

7.2.1 On-body wearable sensor concepts

These initial on-body wearable sensor concepts were created to contribute to the research in two ways; firstly to provide a focused opportunity to experiment with

initial ideas I already had in mind, and secondly to allow me to generate feedback and further ideas with a group of users, in order to inform and inspire the design of the final collections of artefacts (chapter 10). The original intention behind utilising these concept boards within a workshop setting was to contribute to my investigation around form factors, however, due to the use of a diverse range of tactile samples and mock-ups, this workshop also generated important insights into material choices (chapter 6). The concepts were informed by the identification of potentially suitable positions for wearable sensors (section 7.1) and each concept explored design possibilities around one of the eight on-body locations selected. These included the head, face (including forehead), back & neck, armpits, forearms (including wrists), hands (including palms), legs and feet and were deliberately designed to be conceptual and experimental. Key elements used to visualise each concept were secondary research and inspiration images, primary design sketches and illustrations and hand-made mock-ups. In combination with a selection of bought samples, these boards were essential tools for the user workshop described in section 7.2.2.

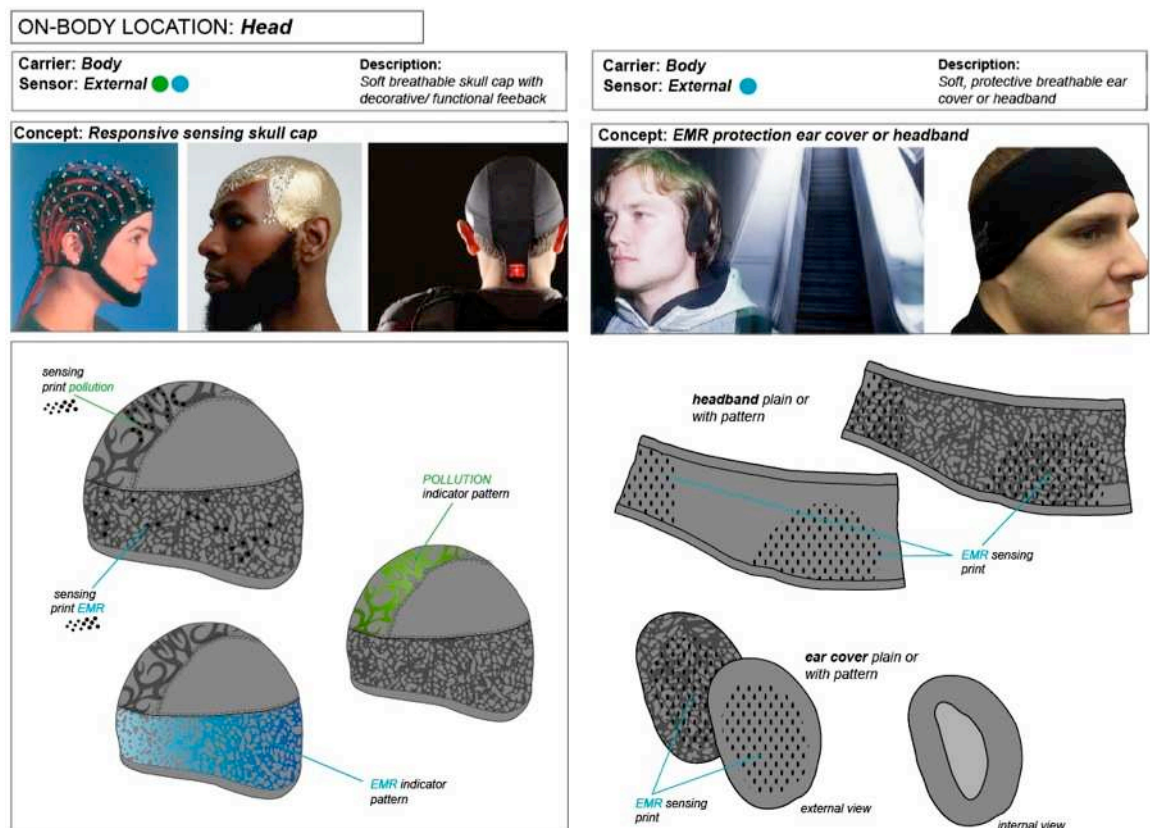


Fig. 7.22: Head-worn sensor concept board, Prah (2014) utilising secondary inspiration and reference images from the Internet (top row) and design sketches, Prah (2014)

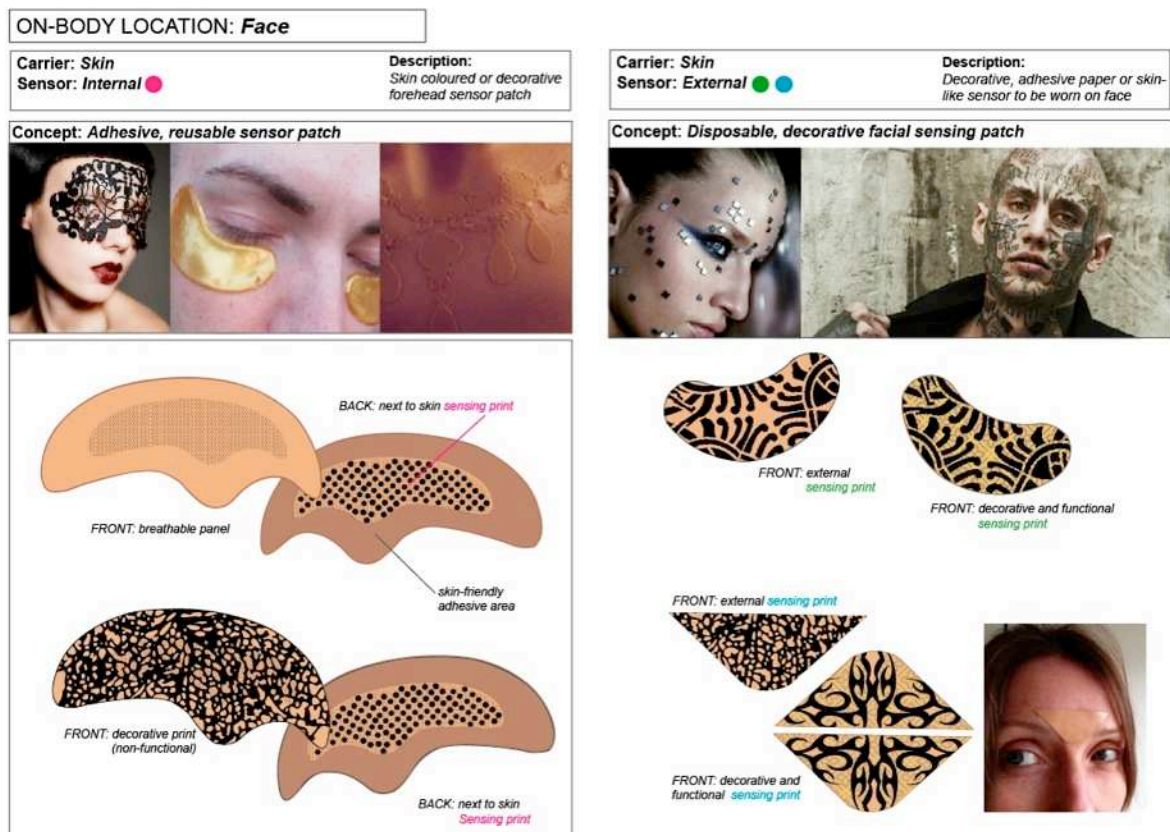


Fig. 7.23: Face-worn sensor concept board, Prah (2014), utilising secondary inspiration and reference images from the Internet (top row), design sketches and wear test image, Prah (2014)

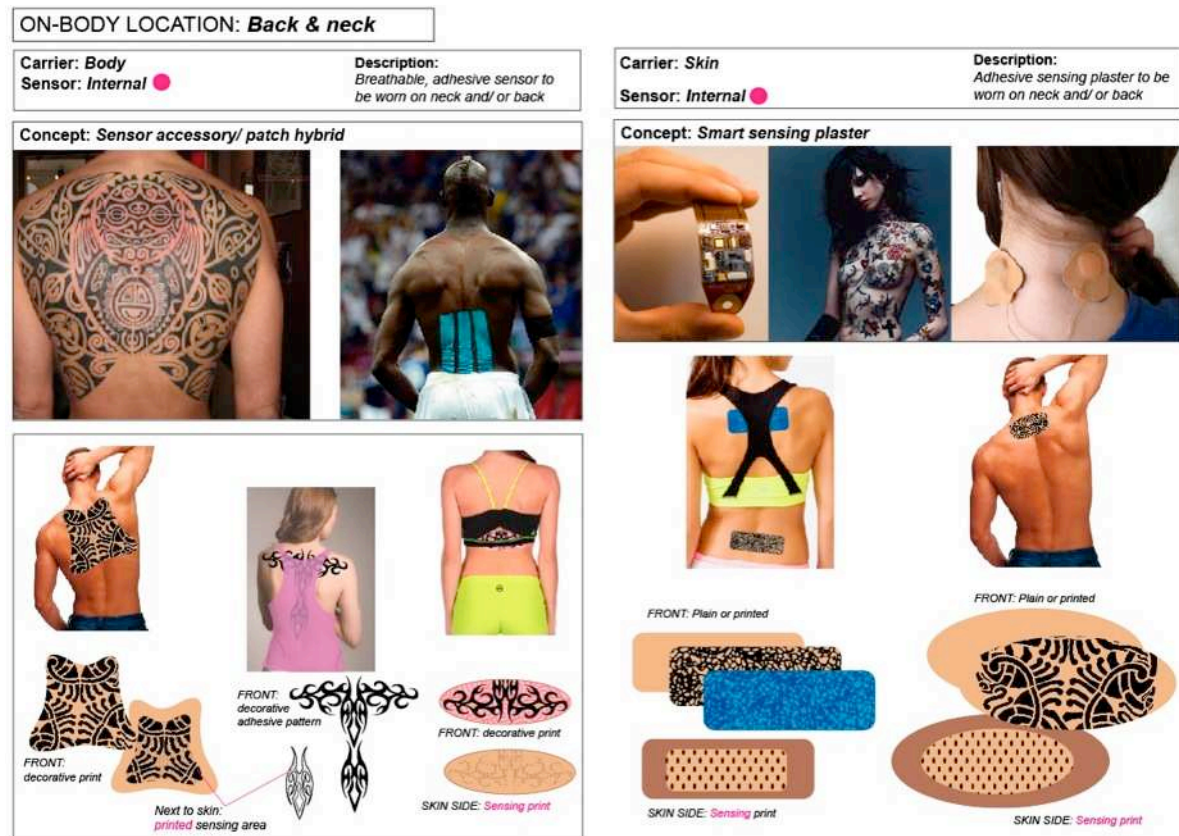


Fig. 7.24: Back & neck-worn sensor concept board, Prah (2014) utilising secondary inspiration and reference images from the Internet (top row) and design sketches and visual mock-ups, Prah (2014)

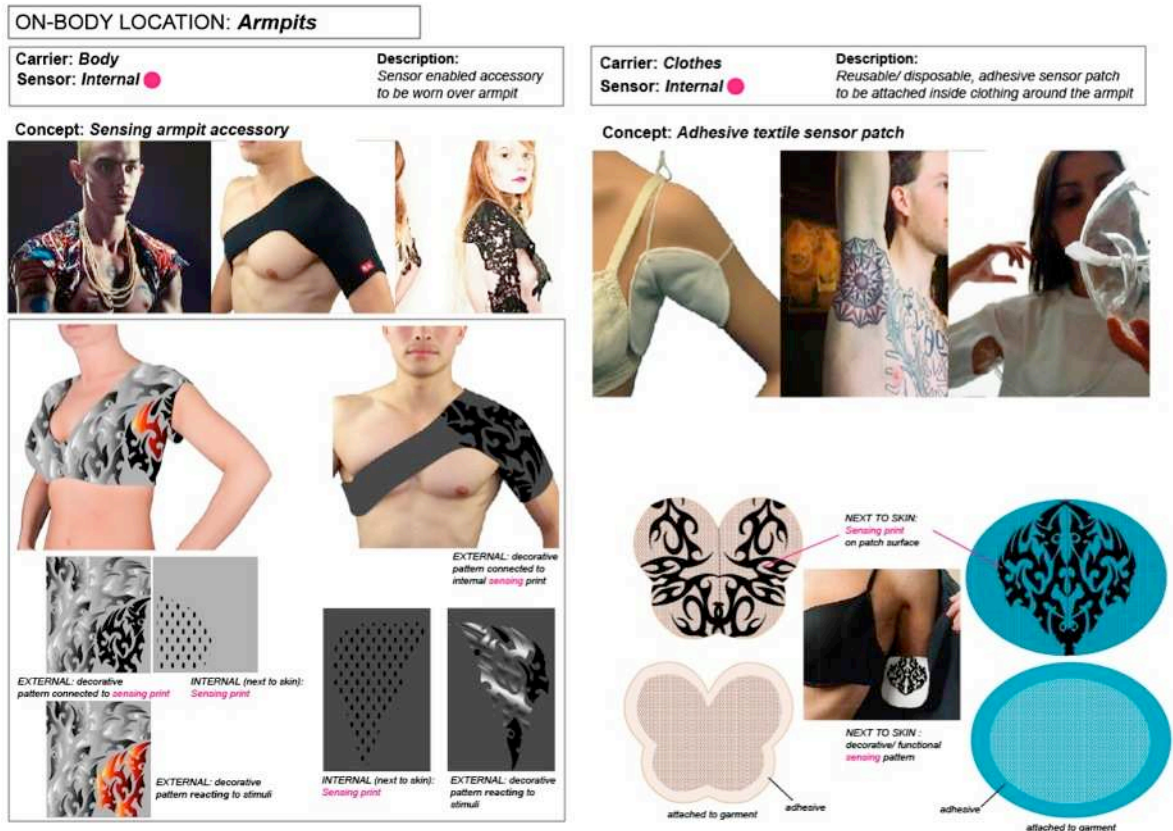


Fig. 7.25: Armpit-worn sensor concept board, Prah (2014) utilising secondary inspiration and reference images from the Internet (top row), design sketches and visual mock-ups, Prah (2014)

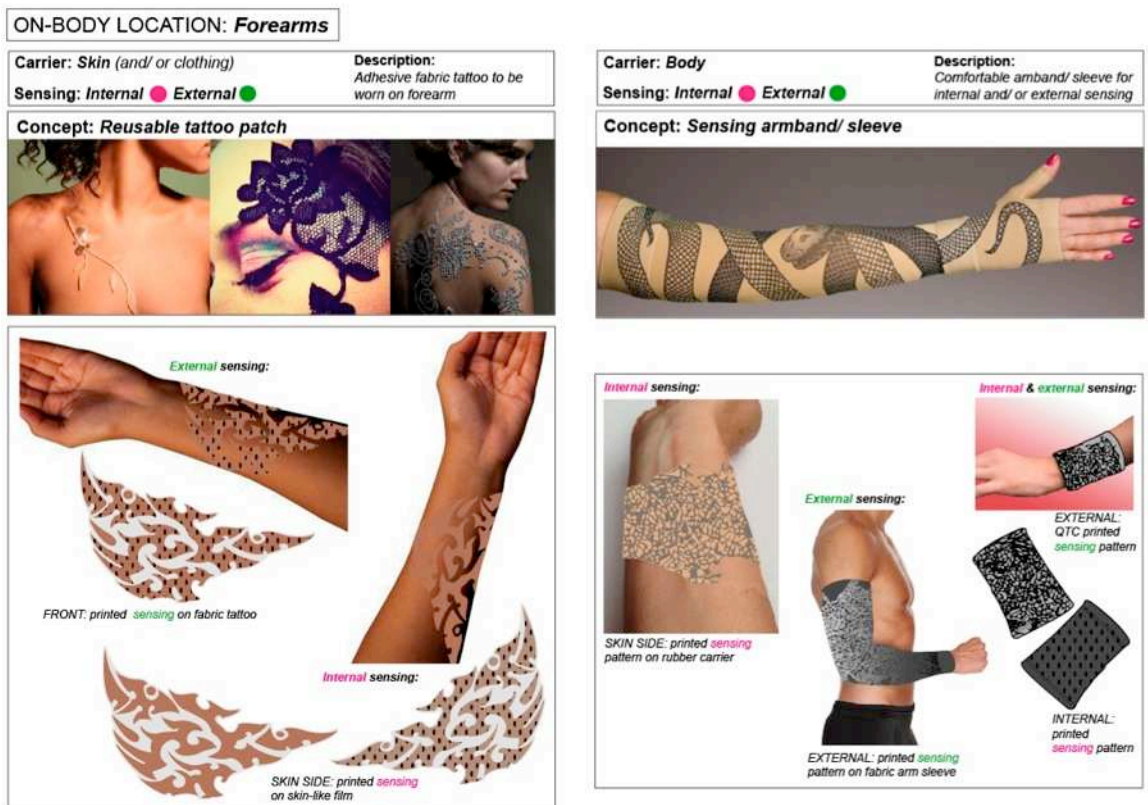


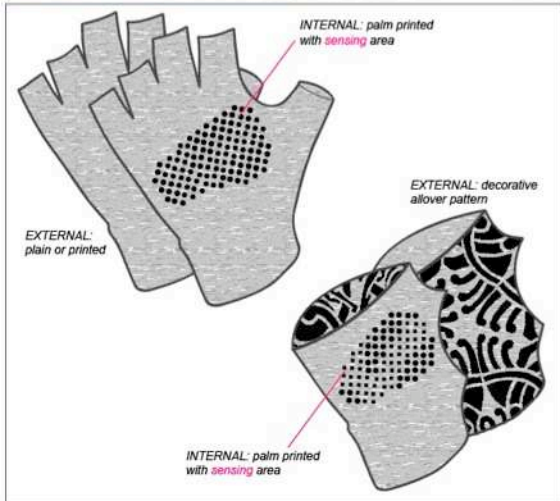
Fig. 7.26: Forearm-worn sensor concept board, Prah (2014) utilising secondary inspiration and reference images from the Internet (top row), design sketches and visual mock-ups, Prah (2014)

ON-BODY LOCATION: **Palms**

Carrier: Body
Function: Internal ●

Description:
Fingerless sensing glove(s)

Concept: Sensing glove



Carrier: Skin

Sensing: Internal ●

Description:
Skin-friendly, adhesive sensing patch to be worn inside palm

Concept: Second skin disposable & customised patch



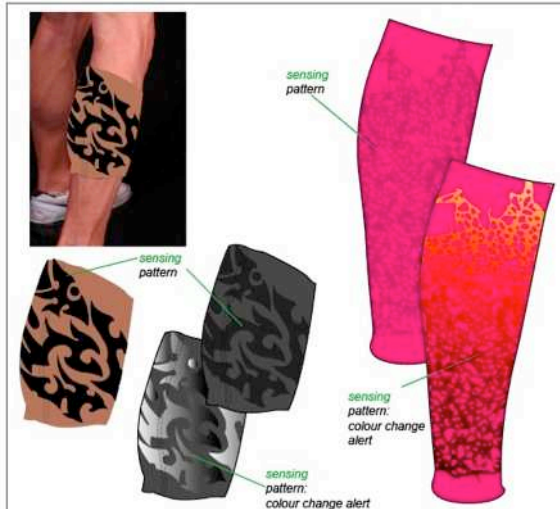
Fig. 7.27: Palm-worn sensor concept board, Prahl (2014), utilising secondary inspiration and reference images from the Internet (top row), design sketches, visual mock-ups and wear test photos, Prahl (2014)

ON-BODY LOCATION: **Legs**

Carrier: Body
Sensor: External ●

Description:
Second-skin calf accessory with decorative/functional pattern

Concept: Reusable calf socks



Carrier: Clothing

Sensor: External ●

Description:
Adhesive pattern sensor to be attached to trousers, leggings etc

Concept: Reusable, adhesive sensor patch



Fig. 7.28: Leg-worn sensor concept board, Prahl (2014) utilising secondary inspiration and reference images from the Internet (top row), design sketches and visual mock-ups, Prahl (2014)

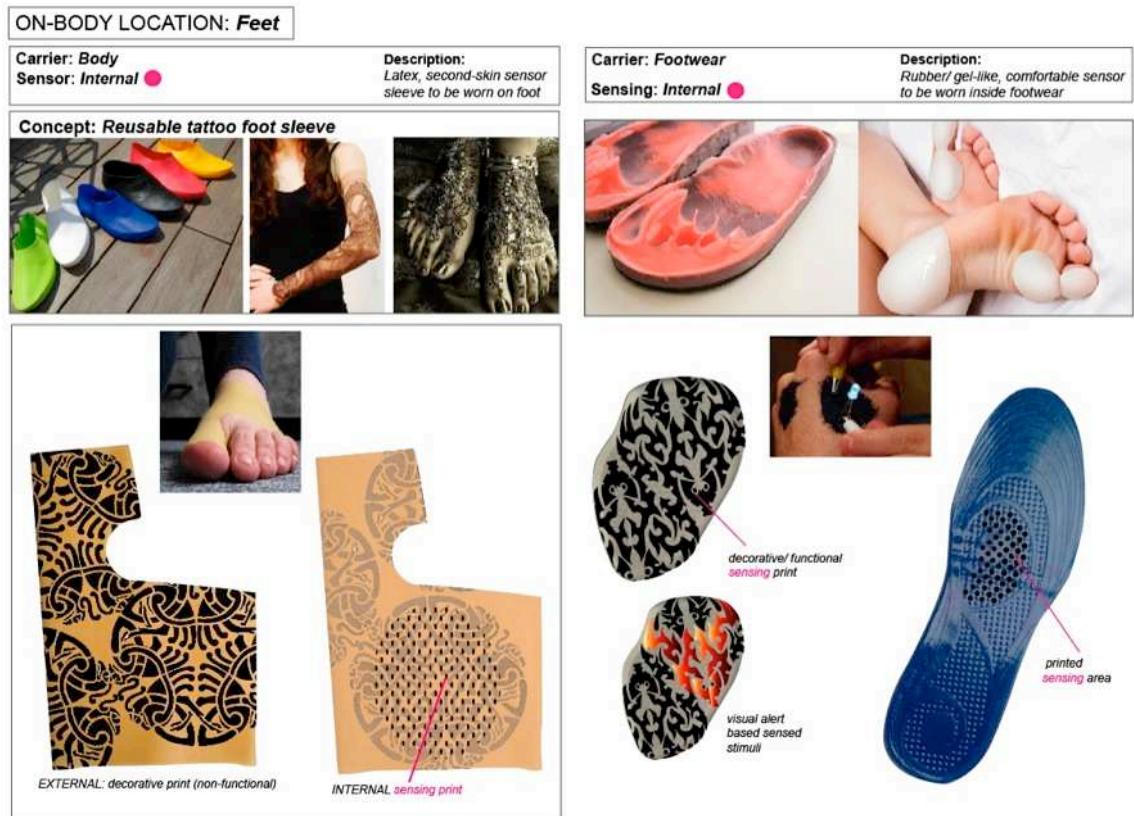


Fig. 7.29: Foot-worn sensor concept board, Prah (2014) utilising secondary reference images from the Internet (top row), design sketches and visual mock-ups, Prah (2014)

7.2.2 User workshop 2: Form focus

User workshop 2 was held at London College of Fashion on the 6th of February 2014 and attended by five participants. The workshop was designed to generate data in regard to both material and form and outcomes relevant to the material investigation have already been presented in chapter 6. With a view to the exploration of form factors, the focus of this workshop was to investigate conceptual devices, which the user would enjoy to wear as part of a preventative lifestyle. Following a brief overview of the research project's background and an introduction to the concept of Wearable Technology with a particular focus on wearable sensors for Preventative Health (fig. 7.30), participants were briefed on the interactive part of the workshop and provided with a short questionnaire (appendix C) to encourage users to evaluate the wearable sensor concepts for their own potential future use.



Fig. 7.30: Workshop introduction



Fig. 7.31: Workshop activity

Participants were further advised that these concepts were speculative and not intended as proposals for ready-to-wear devices and therefore needed to be examined considering potential *future* development, use and wear. Specific attention should also be paid to the suggested on-body positions for sensing devices and their general style and shape, rather than evaluating any particular design aesthetics, which at that stage of the design practice were purely indicative.



Fig. 7.32: Wearable sensor concepts display at workshop



Fig. 7.33: Bought reference samples

Each concept board was supported by a corresponding box of commercially available samples (fig. 7.33) to bring to life some of the design ideas, as well as provide the workshop participants with an opportunity to try out some of the non-technical wearables in order to consider if and how they would be willing to wear

any such products on their bodies in the future. The use of reference samples and image boards had already been employed successfully in user workshop 1 (chapter 8) and the artefacts prepared for workshop 2 were designed and chosen specifically in line with the pre-planned questions to be explored during the user activity and group discussion.



Fig. 7.34: Wearable sensor concepts display at user workshop

Each participant spent time studying each of the concepts and tried on samples where appropriate and available, while I was on hand to answer any potential questions (fig. 7.34). The session concluded with a discussion based on each of the participants' responses to the concepts (fig. 7.35), as they presented their favourite and least favourite choices, which were then deliberated with the group.



Fig. 7.35: Wearable sensor concepts group discussion

7.2.3 User workshop outcomes

The pre-planned workshop activity provided useful insights into potential future user preferences with regard to wearable sensors' on-body location and the outcomes were recorded in the form of written notes during the discussion, as well as by each user in their questionnaires. The following key points are a summary of both:

- Participants agreed that the most suitable on-body locations for wearable sensors would be the forearms, feet and head (when integrated into a hat or helmet)
- Facial patches were considered as too embarrassing to wear and participants were also concerned about face-worn sensors restricting the movement of facial muscles
- It was agreed that back and neck-worn sensors would be too difficult to reach and operate by the wearer
- Palm-worn patches were dismissed as the palms are important interaction and sensitive zones and wearing sensors would restrict this ability (one user commented that wearers would still want to be able to touch, hold and feel objects and people)
- Participants commented that they were interested in the concept that wearable sensors could be designed and worn to be both visible and invisible to others and selected the elastic forearm sleeve as an example which could be worn both hidden under clothing or as a fashion accessory

Additional findings from the user questionnaires included that:

- Users were concerned about potential impacts on their health from outdoor pollution (5/5), indoor pollution (3/5) and EMR (2/5)
- Users would consider wearing a diagnostic health sensor (4/5), pollution sensor (2/5) and EMR sensor (2/5)
- For diagnostic sensors, one of the key reasons to wear such a device would be early knowledge of health threats, as well as monitoring of existing conditions
- Pollution sensors were considered to be useful to contribute to crowd-sourced data and protection from the effects of pollution (2/5)

- Reasons against wearing sensors were cited as concerns about data security and hypochondria (constant worry/ awareness to cause unnecessary concern)

My own observations about creating, presenting and evaluating these concepts as part of the user workshop included the following:

- As the concepts were of a speculative nature, based on the ability to sense and monitor VOCs and EMR from the wearer and the environment utilising emerging and future printed sensing technologies, it was difficult to 'know' specific requirements for sensor wear-times (i.e. minutes or hours) and frequency (i.e. daily, weekly, monthly, bi-annually), as these could vary subject to which aspects of their health the wearer wanted to monitor. Wear-times would further determine wear-situations, which could differ with regard to aspects such as in private/ in public and indoors/ outdoors and I noted that this uncertainty needed to be dealt with when designing and presenting the final concepts.
- The creation of these initial concepts in preparation for the workshop gave me the opportunity to probe initial ideas creatively and without restraint, and while this may have created certain concepts that were unacceptable to potential users in their current form (i.e. sensors worn on the face and the palms), all feedback, whether negative or positive, was seen as highly productive for the next stage of the design practice
- Although the number of participants was relatively low (5), this was not considered problematic, as there was time to go into detail with each participant and engage in a more in-depth group discussion. The collected data (written and audio recorded user feedback and photographs of the event) proved to be highly inspiring and was therefore a significant element of this stage of the design research.

Most importantly, the experience of the design, event and evaluation of this user workshop, contributed to one of the key findings of the research, which is presented in the next section.

7.3 Non-integrated wearable sensors: Skin, body and clothing as sensor carriers

The contextual & literature review (chapter 2), categorised wearable sensors into three groups; *textiles* as the sensor carrier, *clothing* as the sensor carrier and *body or skin* as the sensor carrier, while chapter 3 highlighted the opportunities around the design and creation of *non-integrated* wearable sensor concepts, due to their compelling potential to provide more affordable, accessible and easy to wear on-body monitoring in the context of preventative healthcare.

Following the various design research and practice elements carried out as part of the 'form' investigation presented in this chapter, a more evolved classification emerged, as I identified three key categories of *non-integrated* wearable sensors. These are sensors that utilise:

- *Skin* as the carrier
- *Body* as the carrier
- *Clothing* (including accessories & footwear) as the carrier

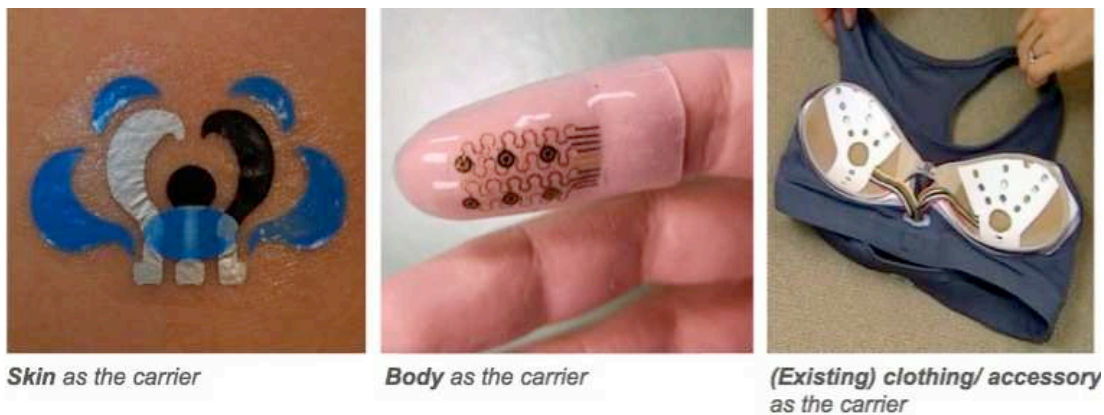


Fig. 7.36: Skin, body and clothing as the sensor carrier, Prahl (2014). Images: (a) skin-worn tattoo-like sensor, (b) body-worn fingertip sensor and (c) clothing attached sensor

7.4 Conclusion



Fig. 7.37: Developed 'form' outcome and focus, Prah (2015)

At the outset of this chapter, I asked the question whether design in response to stimuli locations could inspire new types, shapes and styles of wearable sensors in the context of Preventative Health and it is evident that this approach inspired the creation and generation of impactful artefacts, which explore a broad range of form factor aspects for the design of wearable sensors. Indeed, the evaluation of the diverse range of artefacts and qualitative data produced, subsequently led to the development of a more refined focus on the design and development of three specific types of *non-integrated* wearable sensors, including *skin-worn, body-worn or clothing* (including accessories and footwear) *attached* sensor carrier types and the formulation of this categorisation contributed significantly to the creation of the design brief (chapter 9) and wearable sensor concepts (chapter 10).

The form investigation employed various practice-based methods to generate a varied range of data, which together with the outcomes from the material and function explorations stimulated the subsequent practice (chapters 9 and 10). These methods included: a) basic testing of two types of wearable devices, an experience which produced insights into aspects such as comfort, limited wear positions, security and operational issues, b) the creation of visual diagrams for internal and external stimuli locations, which inspired the idea to design the sensors in response to these locations, c) an extensive visual overview of on-body and location-specific or adhesive accessories suitable for internal and external stimuli, which inspired the design of invaluable artefacts for the user workshop, d) the design of eight on-body

wearable sensor concepts, which allowed me to test initial ideas as part of the design process and generate valuable feedback during the user workshop, and e) a user workshop, which elicited diverse user responses on form factors to inspire the design of the conceptual wearable sensor collections during the final stage of the design practice.

As with the material investigation, the combined use of methods ensured that the generated data concerning form factors was more varied and balanced and the individual findings and concepts produced as part of this form factor investigation could further be used by other designers and researchers as a foundation or inspiration to their own work.

Chapter 8: Examining function through user-centred design

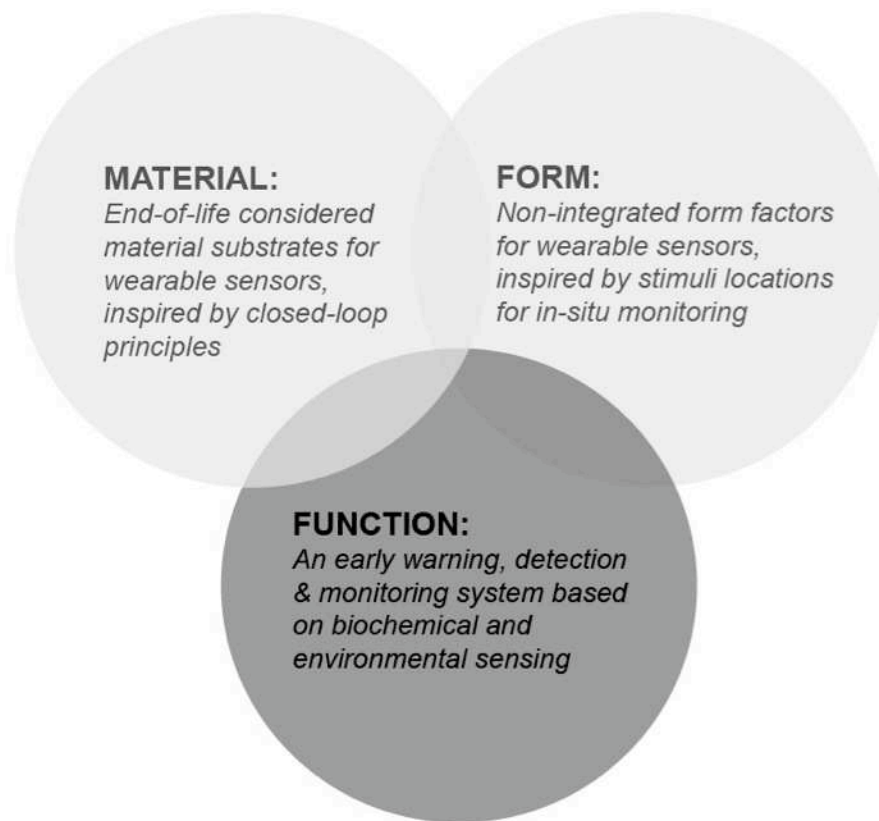


Fig. 8.1: Diagram showing FUNCTION focus as part of three-stranded investigation, Prah (2015)

Chapter 3 emphasised promising design opportunities for wearable sensing devices that can act as an early warning, detection and monitoring system based on biochemical and environmental stimuli, thus enabling the user to take an active role in their health management. In theory, such systems, based on the detection of biochemical and environmental stimuli, could contribute to significant improvements in the field of preventative healthcare by addressing the user's needs to detect early signs of illness or disease, protect them from exposure to negative environmental factors such as pollution and EMR. Moreover, such devices and systems could encourage and motivate the user to lead a more considered lifestyle by avoiding those negative impacts, thus improving their long-term health and wellbeing.

Based on the study of literature and academic and commercial research, developments and consumer products, I am satisfied that there is a genuine need for such early warning, detection and monitoring devices and systems, and that the exploration of new approaches to designing wearable sensors could make meaningful contributions to knowledge. However, any concepts responding to this

identified need have to consider user preferences, lifestyles, habits and existing routines, in order to provide viable and relevant proposals for future devices. It was therefore essential to develop, employ and evaluate appropriate user-centred and PAR methods to be able to create concepts that are informed and motivated by real user needs. Although elements of user-centred research were also utilised in the 'Material' and 'Form' investigations (user workshop 2 was designed to provide data for both enquiries; chapters 6 and 7), the initial idea of engaging the user in this project was driven by the exploration of functional aspects, as I realised the need to connect with potential users in order to inform the design practice.

While the strands of 'Material' and 'Form' had specific research questions to explore, this part of the investigation takes a broader approach and brings together different aspects and enquiries in regard to the functionality of a wearable sensing system, all of which involve the user in their exploration. Working directly with potential users is a well-proven method in academic and commercial design research, which is often referred to as user-centred or human-centred design (Norman and Draper, 1986; Courage and Baxter, 2005; Brown, 2009) and describes the process of integrating potential end users needs, desires and preferences into specific stages of the design process. In practice this means that designers can choose to build and utilise a relationship with users and Fulton Suri (2007), identified the three types of relationships designers and users could enter into as: a) *designing for people*, b) *designing with people* and c) *designing by people*. While *designing with people* describes the approach of learning from people who actively participate in the design process in order to translate their needs, *designing by people* implies that designers act as facilitators, thus empowering potential users to make their own design decisions, based on self-recognised needs. However, it is the relationship of *designing for people* that I am making use of as the framework for the exploration of potential user needs and preferences, and this type of relationship involves studying and consulting people, thus utilising people to *inspire* the design process. In contrast to *designing with* and *by people*, the approach of *designing for people* is based on working with inferred user needs, which means that the user has not expressed any needs directly but that the designer can deduct them from spending time observing or interacting with the user in specific situations and circumstances (*ibid.*).

The concept of utilising the designer-user relationship for inspiration is a key element of this research, however, based on my extensive professional practice, I chose to explore this relationship in order to inspire my own response as a designer,

rather than to co-design with users, or indeed, allowing users to design their own wearable sensors. This was achieved by immersing myself into the culture of a particular end-user and details are described in section 8.1. Indeed, this desire to become conversant with a diverse range of user types (McCann, 2009b) in order to inspire the design practice became the motivation behind the extensive phase of PAR presented in this chapter. Furthermore, it was important to create '*an innovative space*' (Curran, 2012), which could enable the generation of unique primary research and informed inspiration in order to create concepts around the subject of future wearable sensing devices. This approach was particularly relevant, as my intention was to produce speculative, industry-facing, *future* concepts to inspire debate, collaboration and further development beyond the duration of the research project, rather than market-ready consumer products. In addition to working with users, it was also vital to experience the use of wearable sensing devices myself and the theoretical framework for this participatory approach is presented in chapter 4.

8.1 Researching user needs: Quantified Self

The key element of the investigation centred on the approach of PAR, which meant active immersion into a carefully selected and relevant community. As part of my ongoing contextual and literature research in 2012, I discovered the community and movement known as 'Quantified Self' (QS). This term was first coined by Kevin Kelly and Gary Wolf in 2008, when they created the Quantified Self blog and community site ^{8A} in order to provide a platform for global collaboration of users and tool makers with an interest in self-quantification and self-tracking. QS, carries the tagline 'self-knowledge through numbers', and QS participants (also referred to as QSers) are known to engage in gathering, managing, analysing, sharing and comparing personal data, in order to enhance health, wellbeing and quality of life. Other popular terms to describe this phenomenon are 'living by numbers', 'personal informatics', 'self surveillance', 'life-logging', 'personal monitoring' and in extreme cases, 'self-hacking'.

From the first meeting held by the founders in San Francisco in 2008, which was attended by a group of 30 people, the movement has been expanding dramatically, and includes annual conferences in the US and Europe and Meetup groups in 128 cities across 41 countries. These Meetup groups are an important element of the

QS movement and in early 2015 had 42,482 members, of which 11,484 are active. Until recently, self-tracking was considered as an activity reserved to early adopters, but this phenomenon has been growing rapidly over the last five years and has already had a major impact in the field of Wearable Technology, in particular in the Sports & Fitness and Health & Wellbeing sectors, where new types of clothing and accessories, such as activity trackers, smart shirts, wearable sweat sensing patches, sleep and health monitors have been brought to a much broader audience over the last few years (chapter 2).

Mainstream adoption of the self-quantifying trend has also inspired the launch of many new start-up companies, which have been developing and launching a plethora of new devices, software and services aimed at self-trackers and their growing interest in taking control of their own health. Indeed, science and technology futurist Melanie Swan (2012) highlighted the connection between self-tracking, new types of easy-to-use and unobtrusive devices and technologies and opportunities for new health care models in her paper 'Health 2050: The realization of Personalized medicine through Crowdsourcing, the Quantified Self, and the participatory Biocitizen', citing personalised, participatory and preventative medicine as a key factor. Although in 2012 QS was still considered an early adopter trend by many, I anticipated that my immersion in this emerging community would offer a compelling opportunity for original research and inspiration and embarked on this stage of participatory and observational practice, which was underpinned by a thorough desk-based investigation. This preliminary phase of user research included the extensive study of the most recent QS conferences, global QS member Meetup groups, QS community blogs, specialised user and technology blogs and the growing coverage on self-tracking and Quantified Self in the media, including print, online and radio and TV, in order to investigate user behaviours and preferences.

Specific aspects examined included: a) what type of data is generally generated by QSers and why, b) how users manage, display and utilise data, c) what the key existing devices used for self-tracking are and d) how they are currently worn or adapted for wear by the user. The insights generated as part of the first stage of user research were not restricted to the investigation of function, but further provided unique data for other areas, such as the exploration of material and form (chapters 6 and 7).

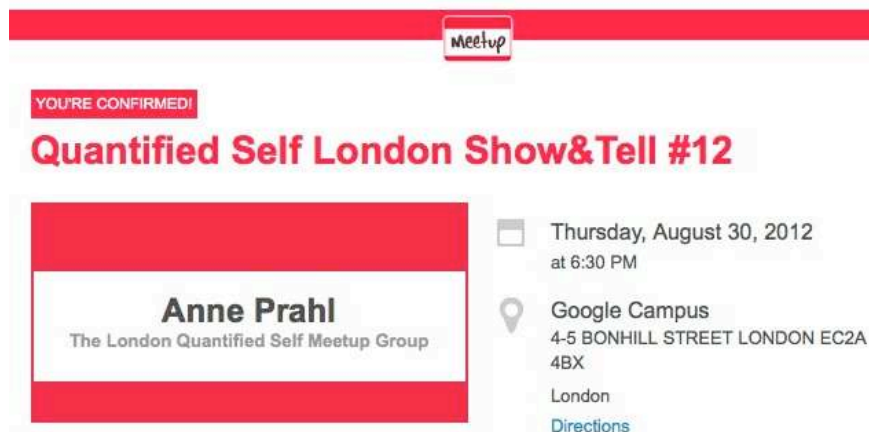


Fig. 8.2: Attendance confirmation of first Show & Tell Meetup in 2012

The next stage of user research involved my active immersion and participation in bi-monthly, so-called Show & Tell Meetups in London, which provided the opportunity to listen to presentations with a focus on personal self-tracking experiences, learn about the various tools and devices available and network with other members during and following the events. I attended my first meeting in August 2012, when member numbers were around several hundred, a number which has grown to 1998 in mid 2015, making the London Meetup Group the 5th largest group in the world. In addition to QS branded events, I also attended other events concerning the use of technology to improve health & wellbeing, which I discovered as a direct result of my immersion in the London based QS culture. These activities were not restricted to one specific period in the research, and user research continued throughout the duration of the project in order to keep up-to-date.

Most importantly I realised that in order to become a genuine member of the community, rather than simply remaining an observer and listener, I needed to participate in and experience self-tracking myself. Although in hindsight this decision can be seen as a key element of the research methodology, at the time it was an intuitive and authentic decision, based on the desire to truly integrate into the community and my growing interest in the pros and cons of self-tracking.

8.1.1 Self-tracking experiment

This experiment proved to be an essential tool in the generation of data for both the form and function investigation. In addition to the issues examined and described in chapter 7, this stage of investigation focused on experiencing and understanding

potential issues and opportunities around utilising self-tracking devices, tools and apps, and subsequently managing the generated personal data into meaningful and actionable information. This activity served a two-fold purpose; firstly, the generation of research data with regards to the general experience of self-tracking in order to inspire design ideas for the wearable sensor concepts, and secondly, the opportunity to utilise the experience and outcomes to create a Meetup ‘Show & Tell’ presentation, which would be shared and discussed with the London QS community for feedback. The latter was to be carried out as an important step to establish trust with members of the community and generate interest in my project, in order to recruit and involve interested QSers in an upcoming user workshop.



Fig. 8.3: Analogue (a) and digital self-quantification and tracking (b and c), 2013

My intense self-tracking phase involved both ‘*analogue*’ and ‘*digital*’ self-quantification, starting off with analogue methods including experimentation with various types of *manual* self-documentation such as visual diary and journal keeping (fig. 8.3 a). This analogue element of the self-tracking phase lasted from the beginning of January to mid February 2013 (6 weeks) and I focused on parameters I could detect without any devices, simply recording any negative personal reactions to mobile phone and laptop use (in view to investigating potential impacts of EMR) and indoor and outdoor air quality. This stage proved to be rather frustrating, mainly due to the fact that I was not utilising any scientific methods but simply relied on my own perception, as and when I noticed anything that seemed to negatively affect me. The generated ‘data’ was subjective and difficult to analyse and this method turned out to be very difficult to keep up.

I therefore moved on to the digital self-tracking phase stage, which lasted from mid February to mid March 2013 (5 weeks) and was carried out in two stages; a digital and ‘double digital’ experience. The first step into digital self-tracking, which utilised

the Fitbit activity tracker, (fig. 8.3 b) lasted two weeks and although the Fitbit was capable of tracking general activities such as walking and climbing stairs, it had no ability to measure or detect pollution. The main aim of this two-week period was to observe my interaction with a digital device and data management on a daily basis. My key observations were noted as frustrations around data parameters (restrictions to parameters set and decided upon by the Fitbit producers) and data syncing and management (this involved nightly, time-intensive downloads to a laptop) and I also felt burdened by the pressure of having to generate data and my reaction to some of the data produced (i.e. distractions from the actual activity of running and obsession with producing 'results' such as weight loss or achieving daily and weekly activity goals).

The 'double-digital' phase, which lasted three weeks, comprised data generation through a combination of digital devices and apps in order to gain an in-depth and first-hand understanding of the specific activities, experiences and issues involved. The Fitbit was used in tandem with an iPhone 5 (fig. 8.3 c), which was further enabled through a range of software applications (apps), in order to make the self-tracking experience more interesting and varied. These included the London Air pollution app ^{8B}, the Juice energy tracker app ^{8C}, the Expereal mood tracker app ^{8D}, the Azumio heart rate app ^{8E} and the Runkeeper app ^{8F}, which were uploaded to turn my iPhone 5 into a wearable tracking and monitoring device. During this stage of the activity, key issues observed revolved around the process of data generation, and highlighted problems of technical incompatibility between devices, distraction by having to interact with devices during activities, and a tendency to obsess about data that had been irrelevant during activities such as running, prior to starting the self-tracking experiment. One of the major concerns recorded was how to interpret health & fitness data correctly, as I was overwhelmed by the generated data and its potential significance and began to wonder if advice and support from qualified healthcare and sports professionals might be required to make the data more meaningful and actionable.

It is important to point out that this self-tracking phase specifically focused on observing aspects of the *experience* and *activity* of self-tracking, rather than being concerned with the detail of the data (such as running performance, heart rate, weight-loss, mood and happiness). As such, this emphasises that the activity of self-tracking was employed as a research tool into the 'how' of using wearable devices and generating data, rather than engaging with the 'what', which is generally the

	ANALOGUE	DIGITAL	DOUBLE DIGITAL
<ul style="list-style-type: none"> accuracy active_passive beyond data customisation existing devices i-quickly-f...ressing.jpg intrusion v freedom lev of integration location neg+pos wellbeing peoplesins...app02.pdf react sense how sense what why smartphone enabled smartphone-apps torgan.ai wellbeing technology whatsawearable 	<ul style="list-style-type: none"> distracted / interference by/ with other stimuli (mem h) -> "dirty data" Can't isolate some of the specific data (i.e feeling unwell due to pollution or health issues) A very subjective way of collecting data, can it be considered real? (scientific), it's all about the quantifiers perception of sth. How can I collect data on invisible/unsmellable pollution - the things I can't even see or feel? How can I quantify the effects on my health? How to visualise invisible data (like smell) (lamp, etc.) What do I know if any per-symptoms relate to specific factors or stimuli? What symptoms to env. What has been achieved through this method other than realising sth is not ok/needs to be changed? (although that is a start) Can a data overlay with digital methods produce better/more accurate results? <p>= FRUSTRATING, DIFFICULT TO STICK TO, BORING</p>	<ul style="list-style-type: none"> PURCHASE <ul style="list-style-type: none"> Choose colour - immediate life to customise SET UP <ul style="list-style-type: none"> Easy to sync with laptop LOCATION <ul style="list-style-type: none"> Show where to wear for accurate measurements Locations during exercise <ul style="list-style-type: none"> EUN - app, parks access Yoga <ul style="list-style-type: none"> Surprising seeing some of the teachers Comeback to tops <ul style="list-style-type: none"> Feels like moving device Feels changing and not doing anything Data provided <ul style="list-style-type: none"> steps, calories, No Yoga data unless logged - frustrations of what are relevant of data learning orientation of data parameters -> the desire to know when yoga was harder data obsession / burnout / lifestyle perspective > more personalised data DATA/DEVICE wearable 	<ul style="list-style-type: none"> flexibility <ul style="list-style-type: none"> weather (un-proof) device covers (uncomfortable/invisible! F/V/G) B) incompatible with constantly upgraded devices OS: Running: Why do I go running? The things I have achieved levels of wellness are not reflected in the data - how can I track the success of my goals? data meaning juggling devices tech in compatibility changing behaviour data silence data distraction DATA VISUALS <ul style="list-style-type: none"> different on device (phone/laptop/desktop) complicated to want to see DATA harder to visualise points more show off?

Indeed, the most valuable data generated during the self-tracking experiment were the observations on how I reacted to the experience and following the completion of the experiment, primary research data (the self-tracking experience itself; 'experience research') and secondary research data (user research based on secondary research tools such as literature and Internet) were recorded into one informal chart (fig. 8.4), before being combined into key aspects (fig. 8.5), relevant to the development of my project.

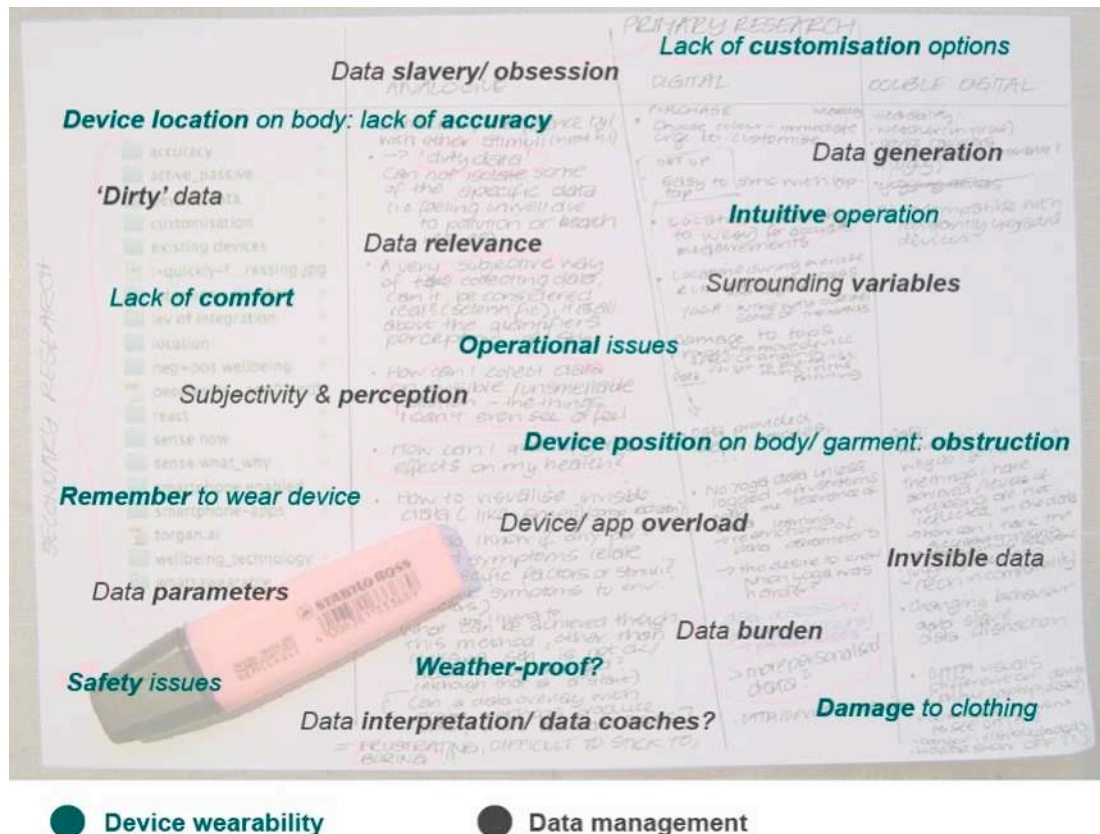


Fig. 8.5: Primary/ secondary research data evaluated into key messages, Praeli (2013)

In order to inform the design process and practice going forward, these findings were evaluated into two main categories, which specifically highlighted the need to focus the design-driven investigation on issues around device wearability (chapter 7) and data management, which involved concerns around *'dirty' or contaminated data* (where data can not be isolated from interference of surrounding stimuli), *data burden* (where the wearer is distracted by or becomes obsessed with the generation of data), *data parameters, relevance and accuracy* (where the user is missing data they are interested in or is uncertain whether the tracked data is correct and how it affects them), *data interpretation* (where the user is unsure how to interpret data correctly or act upon data in an appropriate manner), and *device/ app/ data overload* (where the wearer is distracted by the device or device feedback or becomes overwhelmed with visual information and data).

8.2 Connecting with users & communities

Beside member networking, Show and Tell talks are the main aspect of the popular QS Meetups and following my phase of self-tracking I started on the task of creating

a talk, in order to share my experience with the QS London community during one of the upcoming Meetups. The main aim for giving this talk was to generate interest in my research project in order to recruit members for an upcoming user workshop, with the additional benefit of receiving feedback on specific issues highlighted during my talk, which could further inspire my design practice. Furthermore, through committing to a lengthy period of self-tracking, I could show the group that I was genuinely interested and participating in Quantified Self (chapter 4).

These Show & Tell meetings provide a platform for like-minded people, in order to encourage socialising and sharing of insights into personal tracking for self-knowledge and it was therefore important to honour the spirit of these presentations, particularly as the community experienced increased levels of interest from numerous academic researchers, as well as members with a commercial agenda. Furthermore, these Show and Tell talks have to follow a loosely prescribed format, which was devised by the Quantified Self co-founders in order to keep the talks informal, personal and based on a real self-tracking experiences. Presenters are encouraged to contemplate three key questions in their talks; 'What did you do?' 'How did you do it?' and 'What did you learn?' (Wolf, 2011) and the guidelines for the QS London meet-ups state that presentations should be kept to 10-15 minutes, sharing a personal perspective on an experience with data gathering, self-tracking or analysis. Another important feature of these talks is the Q & A session and customary networking in the pub following the talks.

8.2.1 QS Show & Tell talk 1

As with many of these Show & Tell talks, my presentation was supported by visual slides to make it more engaging and in order to make an obvious connection between QS and my research project, I chose the title 'Self-knowledge through textile-based sensing', which played on the QS tagline of 'Self-knowledge through numbers'. This also gave me the opportunity to briefly set the scene for the audience, as I included a visual introduction to various examples of sensor-enabled textiles. The next step was to convey the general user need for wearable sensors and I outlined the issues around non-communicable diseases (NCDs), including cardiovascular diseases, cancers and chronic respiratory diseases, which can be caused or exacerbated by exposure to outdoor and indoor pollution, toxic chemicals and various types of radiation (chapter 3). The talk then moved on to my reasons for

utilising various self-tracking tools in order to investigate whether this could offer useful insights into the use, design and development of wearable sensing devices for health and wellbeing, before outlining the self-tracking experiment and its key observations, as detailed in 8.1.1. The last part of the talk first summarised the outcome under the motto '*What did I learn...and what did it mean for my research?*', before posing the question whether textile-based sensing could contribute to self-knowledge. In addition to the presentation I also prepared questions and talking points for the Q & A session, to encourage discussion and make sure that the topics I wanted to focus on were covered.

Event and outcomes 1

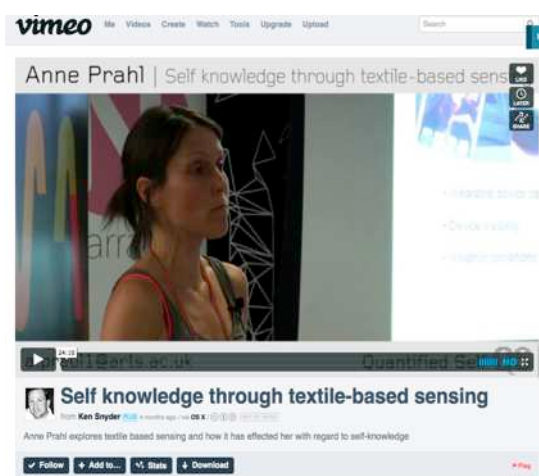


Fig. 8.6: QS presentation on Vimeo



Fig. 8.7: 'Show & Tell' talk at Meetup

The 15-minute talk was given during the London QS group's 17th meet-up, on the 18th of June 2013 and was attended by 112 members. The structured part of the talk was followed by a 10-minute Q&A session, which gave me the opportunity to invite the audience to register interest for my upcoming user workshop and involved a lively debate on a variety of issues around my experience with self-tracking and the concept of using textile-based sensing to contribute to 'self-knowledge', as well as general thoughts and questions from the audience. In order to evaluate this session I was able to make use of a video produced by one of the organisers, in addition to my own audio recording and written notes. Like all QS London Show & Tell talks, the talk was uploaded to the video-sharing website Vimeo (<https://vimeo.com/68775423>).

Although I received several questions about sensors, and the group engaged in an animated discussion about what I had presented, practical feedback for consideration during the creation of the wearable sensor concepts was limited to

comments about the importance of apps to support the function and usability of any wearable sensing system. The most relevant conclusion from this interaction with the group concerned the assumption I had made regarding the group's knowledge and understanding on the subject, based on the expectation that the audience would generally be familiar with self-tracking devices and related technologies. I learned that although many of the QS members participate in some form of self-tracking, this does not automatically mean they are familiar with Wearable Technology or any related subject matters and I therefore concluded that any future interaction with potential users would have to be approached with maximum clarity and simplicity. This initial opportunity to connect with potential future users of wearable sensing devices provided an invaluable tool for clarifying the research in terms of how it should be communicated, defined and presented going forward, and this experience significantly informed the creation of a second Show & Tell talk and development of the QSer workshop (workshop 1).

8.2.2 QS Show & Tell talk 2

Due to an essential period of working on the 'Material' and 'Form' strands of the project, four months passed without any specific focus on the planning of the workshop. However due to a last-minute cancellation I was invited to update the community on the progress of my project, which I saw as a great opportunity before developing the QSer workshop (workshop 1). Having learned from the previous talk not to make any assumptions about what the audience might already be familiar with and considering that these Meetups are attended by many new members each time, my updated talk first recapped on the outcomes of my self-tracking experiment, as presented to the QS community four months prior, before highlighting the potential need for protection from exposure to indoor and outdoor pollution, toxic chemicals and various types of radiation, as well as outlining the emergence of a new generation of digital health tools, such as activity trackers, sensor-integrated clothing and skin-worn tattoo-like sensors, which can be used as part of a Preventative Health approach.

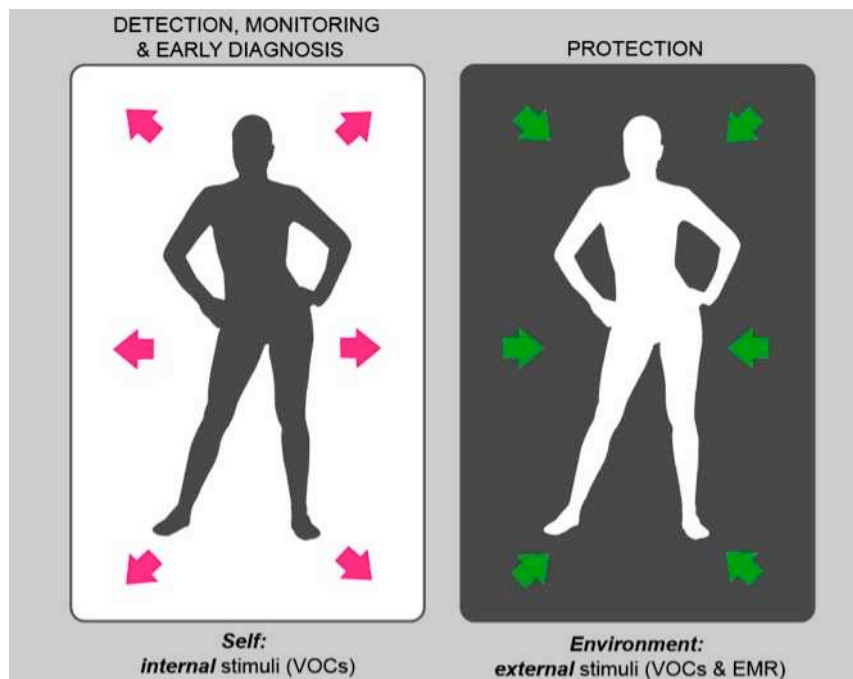


Fig. 8.8: User-need diagram, Prahl (2013)

In order to have control over how I could utilise this opportunity for feedback during the Q&A session, I further built the talk around the key subject I wanted to discuss with the group, which was the exploration of the intended user need. Therefore the aim of this second presentation was to clearly communicate the potential user need for a wearable early warning and detection system in the context Preventative Health and I utilised a previously developed diagram to illustrate my proposal (fig. 8.8), which identified two particular user-needs:

- Detection, monitoring and early diagnosis of *internal* stimuli (coming from the wearer; the 'self') and;
- Protection from *external* stimuli (coming from the environment)

Event and outcomes 2



Fig. 8.9: 2nd Show & Tell presentation and Q&A session, 29th October 2013

The second talk was given at the London QS group's 21st Show & Tell Meetup on the 29th of October 2013 and was attended by 118 members. The talk was designed around two key topics, which I wanted to discuss with the group, before inviting them to my upcoming user workshop. The Q&A session started by questioning the audience on their awareness around potential dangers to human health from the exposure to pollution and EMR and the general response was that people were quite aware of outdoor and indoor pollution, and could even give various examples of devices and apps they had come across. However, with regard to EMR, although some audience members had concerns about potential health impacts, many others remained sceptical, citing lack of evidence as a reason.

Specific feedback from this session included:

- Happy to wear sensors but would like to get advice on what to do with the information (i.e. offering a service)
- Very aware of outdoor air pollution and apps (examples from China)
- Indoor/ office pollution is a definite concern, one suggestion was to have sensors around the office in addition to wearable ones, so the wearer can get a more complete and accurate picture
- Opportunities around crowd-sourced data, which would help with convincing governments to do something about pollution; crowd-sourced data is more powerful than individual information and could empower people
- Apps as an extension to connected devices could offer feedback through the smartphone

As previously, this Show & Tell talk was video recorded and uploaded to Vimeo (<https://vimeo.com/79009267>), which was helpful for the evaluation of the presentation and Q&A session, in combination with my own audio recording and written notes.

8.2.3 QSer workshop (workshop 1)

Relevant outcomes and ideas generated during the investigation thus far were taken forward to inform the planning and design of workshop 1. The intention behind this workshop was two-fold; firstly I needed to probe the theoretically identified user-need for a wearable early warning system based on biochemical and environmental

sensing in practice, and secondly, I wanted to generate unique and diverse data that could inspire the design of the conceptual wearable sensor collections. To achieve these goals, user input was required at the earlier, more explorative stages of the design research, so that this relationship and interaction with potential users could provide the inspiration I was seeking, in order to increase my vision, diversity and creativity as a designer during the final design practice.

Planning & preparation

Planning and preparation are essential elements of successful workshops and the first step was to start the recruitment process, which proved to be extremely work-intensive, although it benefitted greatly from the authentic relationship I had established with the community during previous activities. Other preparation work included the design and selection of suitable documents and artefacts I would need for the workshop, as it was essential to give participants a clear introduction to the research project, create an interesting agenda to keep everybody engaged, and ensure that I generated suitable data, which could be evaluated to inform and inspire the next creative stage in my research project.

Key documents and artefacts utilised during the workshop included an introductory presentation to the project, visual boards and slides to facilitate the first planned group discussion, boards, samples and slides to facilitate the second planned group discussion and a questionnaire to formally record some of the outcomes. The introductory presentation was designed to give participants an insight into the research project, clearly defining how this research connects to Quantified Self and presenting the identified user needs it addressed as part of the wider concept of Preventative Health. The format for this introduction was kept the same as the QS Show & Tell talks, as it had been tested successfully already. The interactive element of the workshop was designed to include the discussion of two pre-determined topics I wished to discuss with the group.

I therefore created and prepared a range of boards and collated reference samples and the first question I intended to address was *'How will the wearable devices alert the user, display and deliver the data?'* and I chose to work with scenario boards to explore this question. Lofthouse and Lilley (2006) describe the method of *'Scenario-of Use'* as a way to explore previously unvoiced needs and desires that are generally not revealed during traditional research, and the concept of utilising future scenarios is a well-used method to simulate and envision future needs and products,

in both academic and industrial design practice. These boards depicted a speculative scenario in 2020, where users take various measures to protect themselves from increased impacts of EMR and indoor and outdoor pollution (fig. 8.10), in order to enable the workshop participants to imagine themselves in a variety of settings and situations in office/ public spaces, at home and outdoors, when contemplating the question.



Fig. 8.10: Pollution scenario 2020: Outdoor, indoor office & public spaces and indoor home, Prah (2013)

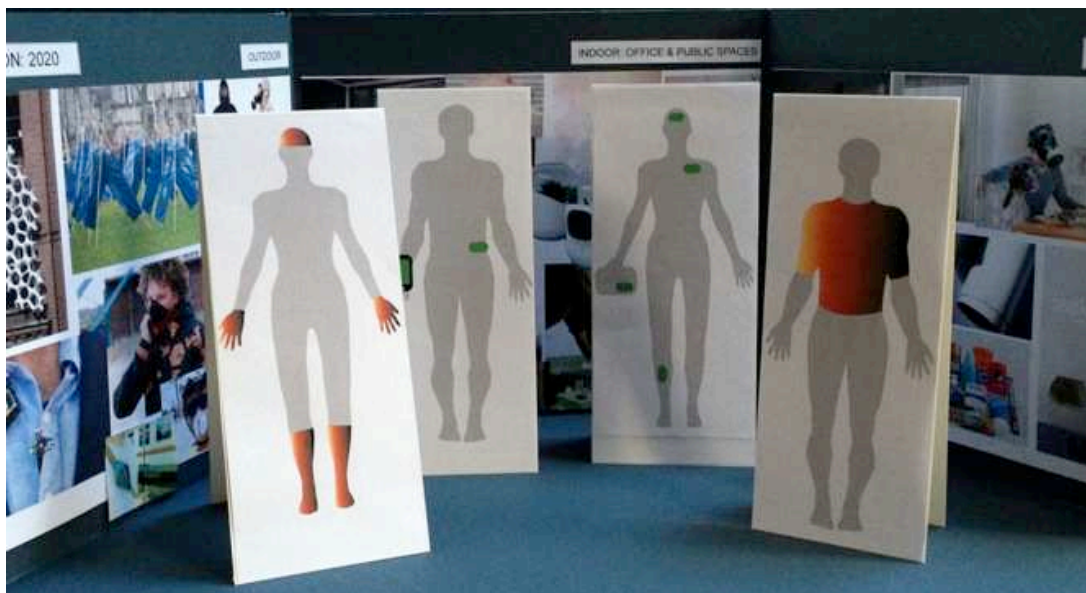


Fig. 8.11: Pollution scenario 2020 with textile-based alert and display options, Prah (2013)

The wearable warning system's alert, display and delivery options in response to the detection of EMR and indoor and outdoor pollution, were illustrated with a group of

figures (fig. 8.11), which showed how the wearable sensor could react visually to detected harmful environmental stimuli through smartphones, accessories, clothing and adhesive patches or tattoos.

These boards were supported by a diagram (fig. 8.12), which explained the various routes for feedback to external stimuli (through the textile-based wearable device itself or in combination with the smartphone/ computer as part of a more complex ecosystem), considering additional aspects such as opportunities of connecting personal environmental data with spatial sensor data and crowd-sourced data to get more accurate and relevant information. A second diagram (fig. 8.13) illustrated the wearable warning system's alert, display and delivery options in response to the detection of internal stimuli (skin-based VOCs), as these may need to be more subtle and would potentially require the input of a healthcare or medical professional. Both diagrams were refined from original diagrams I had previously utilised in the QS Show & Tell presentation, incorporating the constructive feedback I had received during the Q&A session.

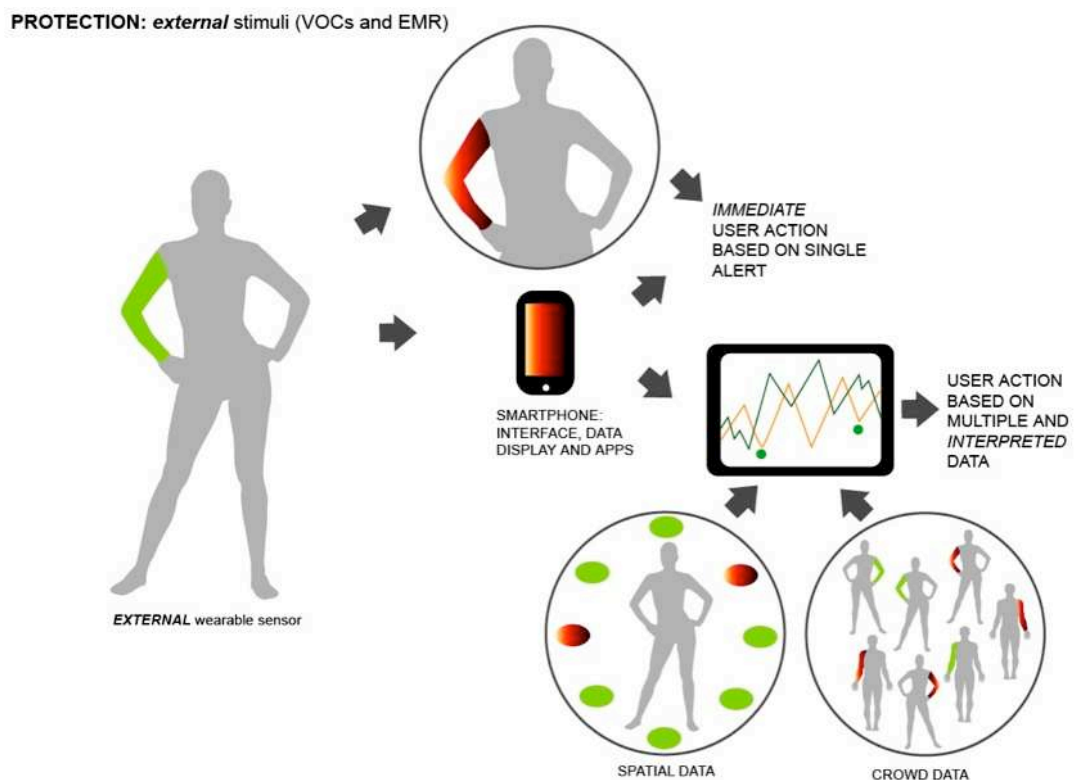


Fig. 8.12: Wearable sensor response to detected environmental data, Prahl (2013)

DETECTION, MONITORING & EARLY DIAGNOSIS: *internal* stimuli (skin-based VOCs)

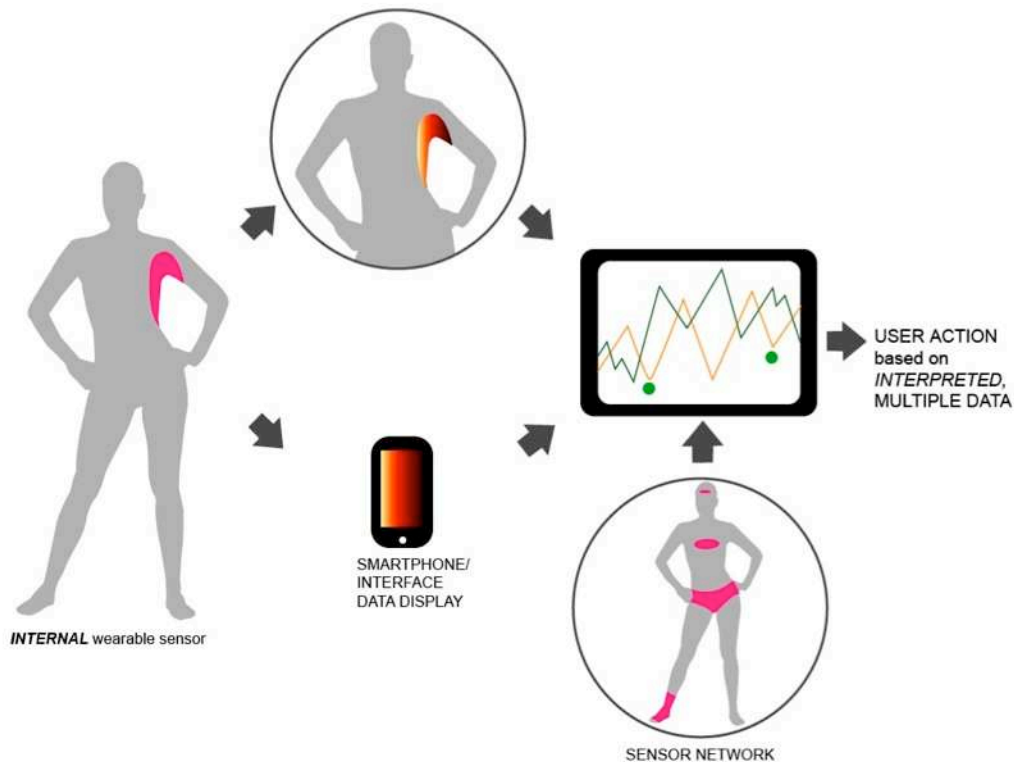


Fig. 8.13: Wearable sensor response to detected internal data, Prahl (2013)

The second topic concerned the exploration of how early warning devices could be designed to make wearing them enjoyable and rewarding as part of a regular routine to enable a preventative lifestyle and I prepared bought commercial samples and boards depicting secondary research examples from the academic and commercial domains (fig. 8.15) to facilitate this discussion. In order to support and complete the data generated during the interactive element of the workshop I also prepared a participants' questionnaire (appendix B) to draw out some basic quantitative data, and capture some of the qualitative data more formally. The questionnaire covered participants' age range, involvement in self-tracking, awareness on potential health issues caused by indoor and outdoor pollution and EMR and use of existing devices in response to these issues, awareness of the concept of Preventative Health and use of related devices. In addition the questionnaire aimed to record preferences on wearable devices alert and feedback options for internal and environmental sensing in different situations and circumstances and probed what actions users might take, based on such alerts.

Workshop event



Fig. 8.14: QSer workshop, December 2013

User workshop 1 was held at London College of Fashion on the 4th of December 2013 and was attended by seven participants, six of who knew each other from previous QS events. Data generated during this workshop was gathered in various ways, including photographs, handwritten notes, a questionnaire and audio recording (and subsequent transcript) of the event. Following the required procedures including participant consent and information, the workshop commenced with my introduction to the research project, which was well received and understood by all participants, before moving into the first pre-determined discussion. This discussion generated many diverse and relevant comments, as participants contemplated their preferences for a wide range of visible and invisible feedback. However, in view of the pollution scenarios presented, participants had many questions around the potential health impacts of EMR, as the scepticism I had experienced during the QS Show & Tell talks, prevailed, while the concept of internal and external VOCs received a more positive response.



Fig. 8.15: QSer workshop boards and commercial reference samples

The second pre-determined discussion relied on a selection of collaged boards and reference samples (fig. 8.15). The samples were tactile, allowing participants to touch and play with a selection of samples including plasters, tattoos, false nails, athletic tape, latex socks and supports and adhesive facial and body-worn patches, many of which are described in detail in chapters 6 and 7. Although some of the female hygiene and beauty items on show were unfamiliar to male participants, the group as a whole responded well to the diverse types of wearable samples, considering material and aesthetic aspects in line with their suitability for future sensors, which could be worn as part of a regular routine.

The final stage of the workshop required participants to fill out the questionnaire, and although the remaining 15 minutes of the workshop soon ran out, participants were so engaged in the topic, that they continued to chat for another hour. Although, this meant that I had failed somewhat in my role as an efficient moderator, I took advantage of this extended opportunity for data generation and potentially unexpected insights, based on the apparent strong group dynamics and participants' interest in the subject, and simply joined into the animated conversation, which by now had almost turned into what O'Reilly (2009) describes as a 'naturally occurring discussion' (2009).

Workshop outcomes & evaluation

This QSer workshop produced a diverse and multi-faceted range of qualitative data, which needed to be analysed and evaluated in order to inform and inspire the next stage of the research project. As there was a large amount of data, some more relevant to my project than other, I focused on the evaluation in line with the topics I wanted to explore, as well as some general points that might inform the ongoing design research.

Key comments in regard to *the wearable device's alert, data display and delivery options* were:

- Alert preferences depend on the situation and don't always need to be obvious (i.e. pulse, vibration, through textile-based device or connected smartphone)
- More subtle/ organic feedback should be considered, even QSers don't always want numbers or factual data

- Extreme or unusual feedback is welcome, the more unexpected the alert, the more likely it is that the user will take action
- Wearable devices could be a way to get away from the smartphone and therefore alerts through the textile-based device make a welcome change, while offering opportunities to be more private or 'show-off', depending on preferences
- Visual alerts (such as colour change, flashing etc.) would need to be easy and clear to interpret

Key considerations in regard to the *design of wearable devices that are enjoyable and rewarding to wear* as part of a regular routine were:

- The concept that one sensor could be provided with a range of accessories so it could be used to create different looks
- Creating Wearable sensors that are 'pretty' and fun to wear, such as jewellery; bringing fashion and technology together to create a 'cool factor'
- Next to skin materials used would need to allow for breathability and comfort
- Customisation and DIY design as an interesting concept for wearable sensors
- The combination of fun, function and value/ cost is important
- Wearable sensors need to work with a variety of outfits, while designs need to be interesting enough so I don't get bored of it
- Wearable sensors need to work with things we wear already (such as underwear), as we don't want to have to create or learn new habits

Key insights about the *general concept of a wearable early warning system* in response to environmental and internal stimuli were:

- Internal (from the wearer) and external (from the environment) sensing are two very different 'stories' and it may prove too complex to design and communicate concepts for both
- Due to lack of scientific evidence, the potential health impacts of EMR are not yet understood by potential users and are therefore difficult to communicate or design for
- Although there is a keen interest in VOC responsive sensing, the actual capabilities need to be made clear to potential users, i.e. they need to be

provided with information on what diseases or health conditions exactly could be diagnosed based on internal VOC detection, as it will affect if and how they will want to wear a sensing device

- The opportunities for wearable sensors as part of a connected ecosystem are significant, while potential users are keen to participate in crowd-sourced data to receive more accurate information on health threats from pollution
- Users may get bored of interacting with the smartphone in the near future, so other modes of interaction might become more important
- Potential concerns about what happens to collected and stored personal health data (i.e. data harvesting or abuse)
- How will relying on device-sensed data affect the user's gut feeling, will we eventually lose the ability to know if we are well or unwell?

In addition to the group discussion, the questionnaire produced some basic quantitative data, although this cannot be considered representative of a broader section of potential users, as the data is based on seven questionnaires only.

Questionnaire summary:

- Seven potential users, five men and two women, ranging from 26-45 took part in the survey
- Six out of seven participants were involved in regular self-tracking with the particular focus on improving health & wellbeing, while five out of seven were aware of specific devices that could encourage healthier lifestyles in the context of Preventative Health
- All participants were aware of the potential health impacts of outdoor pollution, while six were aware of indoor pollution risk and four of potential risks around EMR, while all were concerned about outdoor pollution, five were concerned about indoor pollution and two about EMR, while the remaining five were unsure. All participants were willing to wear a sensing device to protect themselves against the impacts of indoor/ outdoor pollution, while four could see themselves wearing a sensor device to detect harmful EMR
- Three out of seven participants had purchased devices or apps to protect themselves from indoor pollution

- In regard to wearing sensing devices' position on the body, three would prefer to wear a pollution sensor invisible to others, while two are happy for the device to be visible and two didn't mind. Four would want to wear an EMR sensor invisible to others, while three didn't mind and five would want a diagnostic sensor to be invisible, while two didn't mind.
- Concerning alert and feedback options, participants were almost equally as happy to receive alerts to pollution through the wearable device itself or the smartphone, whether at home, in public spaces or outdoors, while they would prefer alerts in response to EMR to come through their mobile phone. The majority of participants also preferred to receive alerts regarding health issues detected from their skin through their smartphone instead of the textile-based wearable device itself.

8.3 Wearable sensors: Blending into users' lives

As highlighted by the various elements of researching user needs, there is strong interest in wearable sensors based on biochemical and environmental sensing and it further transpired that potential users of such future systems and devices are open to several approaches; devices could be part of a more complete ecosystem (where the device's functionality can be extended dramatically through connecting with other types of sensors, users, devices and services and can therefore also respond to sensed stimuli in more sophisticated ways), or sensing devices could work independently to give relatively limited but instant feedback through the wearable textile-based device itself. Perhaps most importantly, the investigation validated my own assumptions, that sensing devices need to integrate into the users' existing lifestyle, routines and outfits to be used regularly and effectively.



Fig. 8.16: Microsoft conceptual sensing bra



Fig. 8.17: Cuff smart jewellery

“Sensors need to work with the things we wear every day anyway. We don’t want to have to learn or create new habits.” (QSer workshop participant, 2014)

Having to create new or change existing routines could be a significant obstacle for the success of wearable sensors for preventative healthcare, and as QSers discussed during the workshop, this could be avoided by making sure that sensors coordinate with the kinds of items that most of us wear everyday already. Indeed, Bergmann and McGregor (2011), also previously identified this need in their paper on body-worn sensor design, which stated that these types of devices should not interfere in the daily routine of the user. Thus, this research proposes that in order for the devices to blend into the users’ lives, they could be worn in two ways; a) attached to existing clothing, accessories or footwear (fig. 8.16), or b) worn independently, to complement an existing outfit (fig. 8.17). Sensors worn attached to the inside of existing clothing, accessories or footwear could blend in as they would be *invisible* to others and would benefit from being worn with items that the majority of people tend to wear, such as underwear, while sensors worn independently, can be worn as a *visible* feature and these could include skin-worn items such as tattoos or accessories, such as jewellery. Furthermore, in order to design wearable sensors that can blend into users’ lives, so that they can easily participate in a preventative lifestyle, wearable sensors need to be affordable, accessible and easy to wear to the broadest section of the population possible, and most importantly, users have to *want to wear them*.

8.4 Conclusion

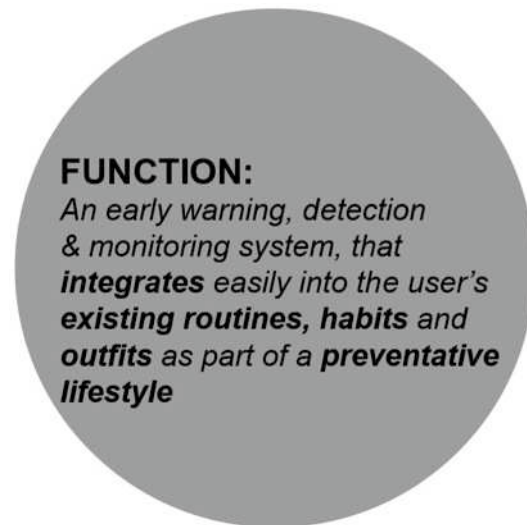


Fig. 8.18: Developed 'FUNCTION' focus, Prah (2015)

At the outset of this investigation, I wanted to explore various aspects around the identified user need for and functionality of a wearable early warning, detection & monitoring system based on biochemical and environmental sensing. These enquiries were addressed through user-centred research methods, which revolved around the immersion into the QS community and the investigation presented in this chapter confirmed user interest in such sensing systems and devices. Based on the diverse range of data generated, gathered and evaluated during this comprehensive phase of investigation, it further transpired that one of the most important elements of designing wearable sensors in the context of Preventative Health is that these devices should easily blend into the users' lives. This need for device integration into user's existing lifestyles goes beyond aesthetic aspects and further considers cost and availability to a broad section of users, while requiring devices that can function as part of a wider ecosystem, able to connect to other sensors and devices the user wishes to use.

The investigation of functional aspects employed various practice-based methods, which included: a) initial and continuous desk-based and participatory research which formed the foundations for the practice-based research, b) a self-tracking experiment, which generated valuable insights into device wearability, data parameters, accuracy, management, interpretation and contamination issues, as well as the potentially negative effects of data overload and dependency, c) two talks based on findings to date, given to the QS community, which produced

presentations documenting the self-tracking experience and links between QS and wearable sensing and this experience further informed and motivated the design of the upcoming QSer workshop, d) an interactive QSer workshop, which generated valuable feedback on users' attitudes towards the concept of wearable sensing in general and sensing device alert, data display and delivery options in particular, and contributed to the overall proposal that wearable sensors need to be designed to integrate easily into the user's existing lives. While the key findings presented in this chapter were combined with the outcomes from the material and form explorations (chapters 6 and 7) to inform the subsequent design practice (chapters 9 and 10), they could also be used by other designers and researchers individually, to provide a foundation or inspiration to their own work.

In addition, the preparation and presentation of my paper 'Wearable e-noses for health & wellbeing: Exploration of a real user need as part of the design process', (Prahl, 2013a), presented at the Wearable Futures Conference at Ravensbourne University, one week after the QSer workshop, motivated in-depth reflection and evaluation of the workshop in particular, while enabling further reflection on the various user-centred methods adapted as part of this investigation, which contributed significantly to planning and writing of this chapter.

Chapter 9: Design brief creation

Through my professional design practice, I have learned to appreciate the importance of an adequate design brief and it was therefore essential to develop an appropriate design brief, which could embed the relevant findings collected and generated through the practice-based investigation of material, form and function (chapters 6,7 and 8), in order to provide the direction and inspiration behind the design of the conceptual wearable sensor collections (chapter 10).

In an industry context, the majority of design jobs respond to a design brief developed by a client or senior management and with a particular view to the design of clothing and accessories, these briefs often consist of information about the styles and colourways required, materials to be used and price points, however design briefs can vary dramatically, depending on the type of product to be designed. McCann (2009), states that an inspiring and informative design brief is an essential point of reference, which is directly responsible for any design outcomes. In a speculative context this point of reference becomes even more important, and as many practice-based PhD research projects, including my own, are based on conceptual frameworks, there is great freedom in what the design researcher can design or make. Although other designers may disagree as they feel it would stifle their creativity, I believe that particularly in speculative projects, it is essential to have a clear vision and focus. I therefore utilised the design brief as an effective tool to create the necessary boundaries for this project in order to concentrate on the creative challenge in hand and to create a body of work that could contribute to new knowledge in the specialist field of wearable sensor design.

This project is based on the understanding that extensive research *prior* to the formulation of the design brief is the key element in creating a highly informed and inspiring design brief, which could subsequently lead to more diverse and relevant design outcomes. This method allows for the identified gaps of knowledge to be integrated into the design brief, so that they can be further explored in great depth as part of the design of the wearable sensor collections. In particular view to the end-of-life issues identified, my approach involves the natural embedding of potential solutions in the design brief. This opportunity for early intervention and integration of end-of-life considerations into the early stages of the design practice and process (i.e. concept and inception) plays a significant role within my project, as I believe that designers cannot 'fix' an inherently unsustainable design brief.

Moreover, this approach has also previously been identified by other researchers and practitioners as the point of intervention (Walker, 2006; Bhamra and Lofthouse, 2007; Sherwin, 2012 and Köhler 2013). I further agree with Walker (2006, p. 12), who stated that *‘Critical thinking and the challenging of precedents and standards must begin to prefigure the design process...’* so that pre-determined environmental considerations can become an integral part of the design process (*ibid.*).

9.1 Design brief development

The creation of the design brief was a key practice-based method (chapter 4) and its comprehensive research, development and creation made up a considerable part of the research, stretching over the first two and a half years of the project. In particular, the design brief was informed by the three-stranded design investigation into material, form and function (chapters 6, 7 and 8) and merges the outcomes, insights and research questions, to provide the much-needed boundaries for the final stage of creative investigation, in this complex field of design research. These included: a) the probing of diverse material aspects highlighted that there were compelling opportunities to explore what a ‘wearable material’, rather than a conventional textile, could constitute, with a particular view to exploring rubber-like, paper-like and felt-like synthetic or natural nonwoven substrates, which could be recyclable or biodegradable, b) the exploration of form factors determined that new types of easy-to-wear skin or body-worn and clothing-attached wearable sensors could be designed in response to stimuli locations and c) the preceding investigation of functional aspects highlighted that users were indeed sympathetic to the concept of wearable sensors based on biochemical and environmental stimuli, but needed these devices to integrate into their lives easily.

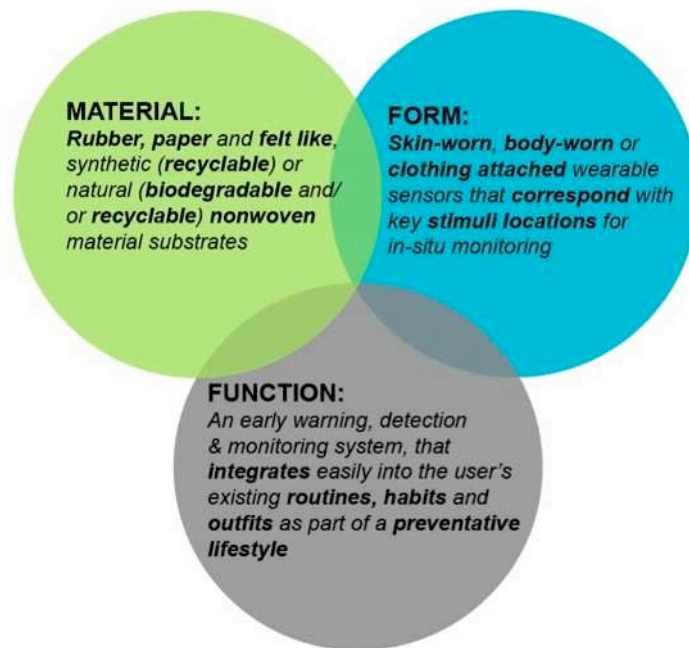


Fig. 9.1: Design boundaries & focus for final artefact collection, Prah1 (2014)

Combining the three strands' individual research outcomes into one creative investigation for the final stage of the design practice (fig. 9.1), this investigation explores *how* to design wearable sensors that could easily integrate into the users' diverse spectrum of existing routines, habits and outfits. The challenge of successful lifestyle integration and subsequent user adoption is examined through the development of closed-loop inspired nonwoven synthetic and natural material concepts and the design of non-integrated skin-worn, body-worn, and clothing attached wearable sensors, while considering a multitude of user preferences for functional aspects such as which types of stimuli they might need to detect and monitor, the level of interaction they choose to have with the device, the type of feedback they prefer and whether they wish to connect to a wider ecosystem, which could make use of additional sensors, devices and services to benefit the user.

9.1.1 User types

When asked what makes tracking and sensing devices truly wearable during a debate at the Wearable Technology Show 2014 in London, Gareth Jones from Fitbit UK commented that devices need to sync with people's lifestyles in order to be successful (Jones, 2014) and this statement mirrors my own findings with regard to the need for integration into users' existing lifestyles (chapter 8). However, to be able to design devices that correspond with people's diverse preferences and

routines, designers must consider the broad range of potential users types varying greatly in lifestyle, age, technology affinity, aptitude, health situations and compliance, unless their concepts or products are deliberately aimed at a particular niche consumer only.

In line with a user-centred approach, design and technology companies often utilise specifically identified and developed user profiles as part of the briefing, design and development process, in order to better understand and cater for the different needs of the potential users of their future products or services. In their book '*Understanding your users*', Courage and Baxter (2005) provide methods, tools and techniques to practitioners who are involved in the design and development of products. They believe that understanding existing or potential users and their needs is the most important element of designing and developing a successful product, while a lack of understanding is likely to lead to failure and outline three key steps in the context of user-centred design, which include the development of user profiles, personas, and scenarios. The authors further describe that user profiles are concerned with aspects such as demographics, skills and occupation, and are utilised as a tool to understand who a product is being developed for, while personas can be described as fictional individuals created to represent archetypes of end users based on the user profile, and scenarios are stories that describe how the fictional persona might interact with the product in particular situations (*ibid.*). Design practitioner and author Alan Cooper introduced the concept of personas as part of his goal-directed design methodology (Cooper, 1999), which focuses on various goals, behaviours and needs of end-users as part of the design and development process.

In the specific context of designing consumer health technologies, Associate Professor of Health Management & Policy at Saint Louis University and colleagues LeRouge *et al.* (2013), state that the use of user profiles and personas to design and develop new concepts and products has been neglected in the past, and hence, that many new products designed to empower the consumer to actively manage their health, have low adoption and usage rates. LeRouge *et al.* (*ibid.*) utilised the methodology of developing user profiles and personas and demonstrate that this method could be a valuable approach in understanding a diverse group of potential users and subsequently informing the design and development decisions.

Building on this approach, rather than utilising user profiles, which are critical elements in professional practice and often used to recruit usability testing once the product has been designed (Courage and Baxter, 2005), my method, in line with the speculative nature of the project and the fact that I am not designing user-facing finished products, utilises the combination of user types and fictional scenarios. My speculative user types, which are introduced further on in this section, were placed in imagined scenarios (section 9.2) to create user type concepts and are grounded in my preceding research based on an iterative process (*ibid.*). This process included a broad range of research methods including familiarising myself with the product and related research (chapter 2), identifying related gaps in knowledge and design opportunities (chapter 3), learning about the product, its use and my potential users through ethnographic research and design practice (chapters 6, 7 and 8) and refining the user types and stories to act as the design brief, as presented in this chapter.

Recent examples in the field of electronic consumer products include a technology user typology developed as part of the Pew Research Center's Internet & American Life Project, presented in the report 'The Mobile Difference' (Horrigan, 2009). The authors of this report distinguished technology users based on their assets (the gadgets and services they have), actions (what they do with what they have) and attitudes towards the integration of technology devices and gadgets into their lives. This typology included the identification of ten user groups, ranging from 'digital collaborators', 'ambivalent networkers', 'media movers', 'reviving nodes' and 'mobile newbies', to 'desktop veterans', 'drifting surfers', 'information encumbered', 'the tech indifferent' and 'off the network' (*ibid.*). Specialist online platform PC Mag identified the most common technology types as the Outdoor Enthusiast, Apple Fanboy, Business Traveller, Executive, Gearhead, Tech-Savvy Mom, Gamer, Bargain Shopper, and DIYer (Jacobsen, 2011), in order to highlight the diverse range of needs within the technology-using community.

Above typologies were inspiring tools for the creation of my own user types and concepts, while another valuable reference was the technology adoption lifecycle, which was developed by Everett Rogers and colleagues at Iowa State University in 1957 and further developed for broader use by Rogers in his book 'Diffusion of Innovations' (Rogers, 1962). This lifecycle describes how and why the general public tend to adopt or accept a new technology and is based on Rogers' innovation adoption curve (*ibid.*), which is a model that differentiates between adopters of

innovations as innovators, early adopters, early majority, late majority and laggards. In addition to these five types of innovation adopters, it was also beneficial to study the various identified user attitudes towards technology, and the main types often discussed are technophobes and technophiles. Technophobes are generally described as people with an aversion to or even fear of technology, and therefore might avoid the use of it. In contrast, the technophile is generally enthusiastic about new technology, considering its adoption and use as an improvement of a broad variety of life and social problems. In addition to these two contrasting and well-accepted relationships between people and technology, techno-luddites (Brosnan, 1998, p. 156) are understood to be opposed to, or very slow to adopt new technologies into their lives, and unlike technophobes are not necessarily fearful of technologies but want to make sure that technology and its use is democratically controlled, so that the public can decide if, how and when to use it, rather than having it forced upon them (*ibid.*). In a similar vein, techno-sceptics are not against technology per se, but question its use and want evidence that it will bring meaningful advantages for the user.

Building on the five types of innovation adopters, my own user types are further based on the diverse research findings concerning material, form factor and functional aspects and are particularly inspired by the phase of active immersion into the QS community and interaction with other users. These user types naturally fitted into five different categories, thus producing five different speculative user type concepts, which I classified as the *technophile*, the *technoista*, the *technoDIYer*, the *technosceptic* and the *technophobe*. It is clear that there is a far broader spectrum of potential user types than the five presented in this research and that user types can cross over and change depending on situations and circumstances. However, the decision to focus on these disparate types aided the development of five distinct user concepts, which explored the potential needs and preferences for future wearable sensing devices, in order to potentially engage a wide range of users in a preventative lifestyle. The premise that bands these five user types together, is that in their own ways they are all keen to utilise new tools to enable a preventative lifestyle in order to improve their long-term health and wellbeing, and can therefore all be described as 'Proactive Health Consumers', a subculture of consumers who are keen to be more informed, proactive and empowered in regard to their own health (Havas Worldwide, 2012).

9.1.2 Artefact criteria

The extensive definition phase of research and practice (chapters 6, 7 and 8) generated a significant amount of data, much of which could be considered relevant to the design and development of the final artefact collection. My intention was to integrate previous findings in the artefacts, so that they could embed and present the diverse ideas and outcomes in an stimulating way, in order to be used as tools to inspire future innovation in the field of wearable sensors. I therefore devised a method, which allowed me to ensure that selected key findings could be embedded and explored within the five conceptual wearable sensor collections. This method was based on the notion that the five user types; *technophile*, *technoista*, *technoDIYer*, *technosceptic* and *technophobe*, could act as a lens or filter through which the key elements of the extensive body of research data could be presented.

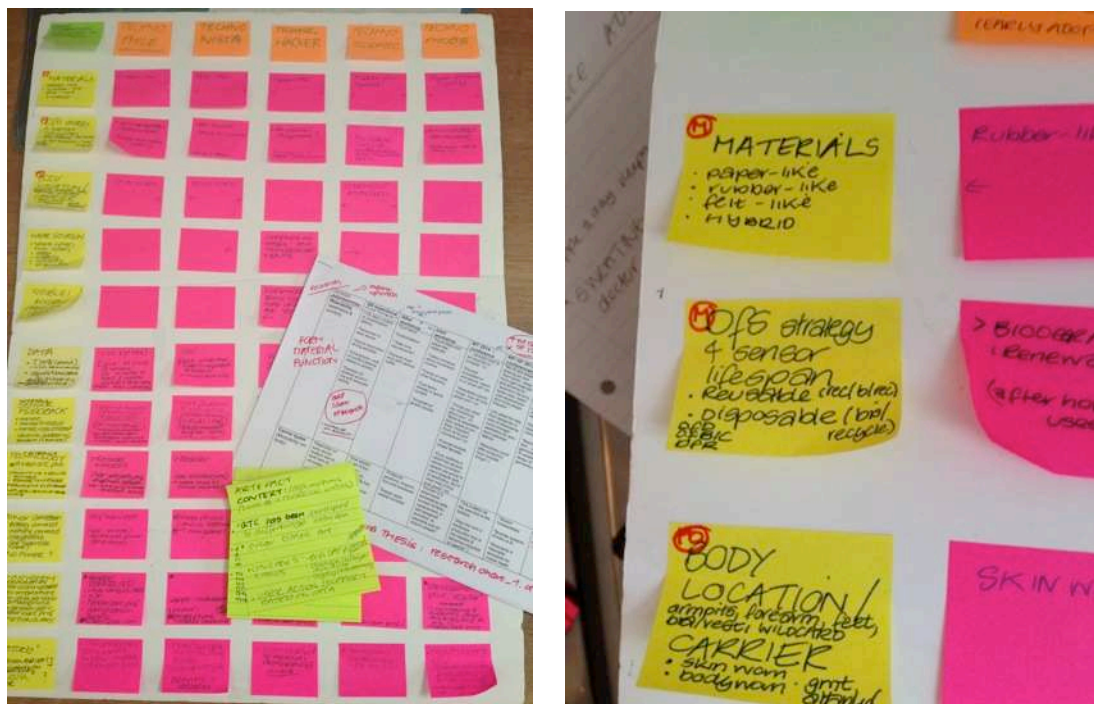


Fig. 9.2: Artefact chart board, work-in-progress and close-up, Prahl (2014)

I created a simple 2-axis chart (fig. 9.2), with the five user types on the x-axis and eleven selected artefact criteria on the y-axis. This chart went through several layouts and versions, as the focus on the selected artefact criteria narrowed down from eleven to six final criteria (fig. 9.3), which I considered a manageable number as part of the design challenge.

	techno_phile Body & skin extension	techno_ista Customise & accessorise	techno_DIYer Makers & fixers	techno_sceptic Slowtech Mindful	techno_phobe Low-tech Analogue Back to basics
MATERIAL SUBSTRATE: TYPE	RUBBER-LIKE: • synthetic	PAPER-LIKE: • tech paper/ synthetic	HYBRID: • rubber/ paper • natural	HYBRID: • felt/ rubber • synthetic and/ or natural	PAPER-LIKE: • bio paper • natural
EOL CONSIDERED NONWOVENS					
MATERIAL SUBSTRATE: EOL OPTIONS	• reusable • recyclable	• reusable • recyclable	• reusable • biodegradable	• reusable • recyclable or • biodegradable	• biodegradable • recyclable
FORM: ON-BODY LOCATION	• forearm • foot/ sole	• back/ neck • forearm • foot/ sole	• head • armpit	• movable • foot/ sole	• forearm • back or other invisible
NON-INTEGRATED IN-SITU SENSING					
FORM: CARRIER TYPE	• skin/ body worn hybrid • visible/ invisible?	• skin-worn (adhesive) • visible	• body-worn • visible	• clothing attached • invisible	• hybrid? (skin/ body/ attached/ hand-held) • visible/ invisible
FUNCTION: USER NEED/ STIMULI TYPE	• biochemical • sensor network/ apps/ devices • self-centric	• biochemical • environmental? • connect to social media/ devices	• biochemical & environmental • sensor networks/ crowd-sourcing	• biochemical • contribute to research	• biochemical • personal focus/ no connections
EARLY WARNING SYSTEM					
FUNCTION: UX: FEEDBACK & INTERACTION	• on-demand/ feedback options • holistic scientific data; networks/ apps/ devices	• visualise data • aesthetic data/ feature • textile and device feedback	• DIY data visuals/ data connection • textile and device feedback	• analysed device feedback only/ no distractions/ worries	• no data feedback to user/ all data to healthcare professional • external reader

Fig. 9.3: Final artefact chart diagram, Prahl (2015)

These final six criteria were split in line with the exploration of material, form and function and comprised:

- Rubber-like, felt-like or paper-like substrate (*Material*)
- End-of-life option, i.e. biodegradable or recyclable (*Material*)
- On-body location for in-situ sensing (*Form*)
- Carrier type, i.e. skin-worn, body-worn or clothing attached (*Form*)
- Stimuli type, i.e. biochemical/ environmental (*Function*)
- User experience, i.e. sensor feedback and user interaction (*Function*)

Each field under the five user types and to the right of the relevant artefact criteria of *MATERIAL*, *FORM* and *FUNCTION*, was concerned with a specific corresponding design feature in line with the particular user type. This systematic approach was necessary to ensure that the relevant key findings and ideas could be embedded

into the artefacts and create five diverse collections. However, I was aware that this chart would serve as a general guideline and that it was likely that some elements would change and evolve during the design process, as I became 'more familiar' with my speculative users and their preferences through creative exploration including the design of mood, textile and colour boards (chapter 10).

9.2 Design brief: User type concepts

This design brief consists of five divergent speculative user types, which were created to evoke a multi-faceted design response during the final stage of design practice. Each user type concept was developed on a selection of criteria, which included:

- Who is the user?
- What are they looking for in a wearable sensor?
- What kind of other technologies, devices or tools do they use already?
- User experience: what kind of feedback and interaction are they looking for?

As previously mentioned, all five speculative user types are proactive and informed about their health and well aware of the potential benefits of participating in a preventative lifestyle to enhance their long-term health and wellbeing, and are therefore willing to consider the integration of a wearable early warning, detection and monitoring system into their lives. They do however vary in terms of their attitudes towards and preferences for these types of devices, thus requiring a highly personal design response to their hypothetical potential needs and wants.

Furthermore, based on my qualitative research findings in regard to potential users, I decided that all five stories would be unisex and that the age range would be relatively broad (20-65), in line with the QSers and users I engaged with during my immersion in the community. In order to visualise the user types and their potential needs as part of the design brief, I utilised reference images from the Internet covering a broad range of sources including commercial, academic and personal websites and blogs and fashion and technology magazine images and combined these images with fictional quotes, which were carefully crafted to reflect the diverse range of user needs and preferences I had identified during my research.

Techno_*PHILE*



Fig. 9.4: User concept *technophile*, Prahl (2014): (a) Google Glass, (b) Proteus ingestible sensors, (c) UCSD sweat sensor, (d) The third hand (Stelarc), (e) Skinput: body as an input surface

Technophiles (fig. 9.4) consider themselves explorers of new technologies and are keen to be the first to try new gadgets and devices, putting them ahead even of early adopters, as they try to get their hands on the latest devices, preferably still in the development stages. They were early adopters of the first generation of self-tracking tools and are still using a selection of health and wellbeing devices and apps, but are now impatiently waiting for the opportunity to test ingestible sensors, which they believe is the future of health-related sensing. In the meantime they are happy to try and test any wearable sensors that can become a natural extension of

their body or skin, as long as they are set up to connect to their other devices and provide flexible and context-aware feedback and interaction as part of a wider ecosystem.

Techno_ISTA

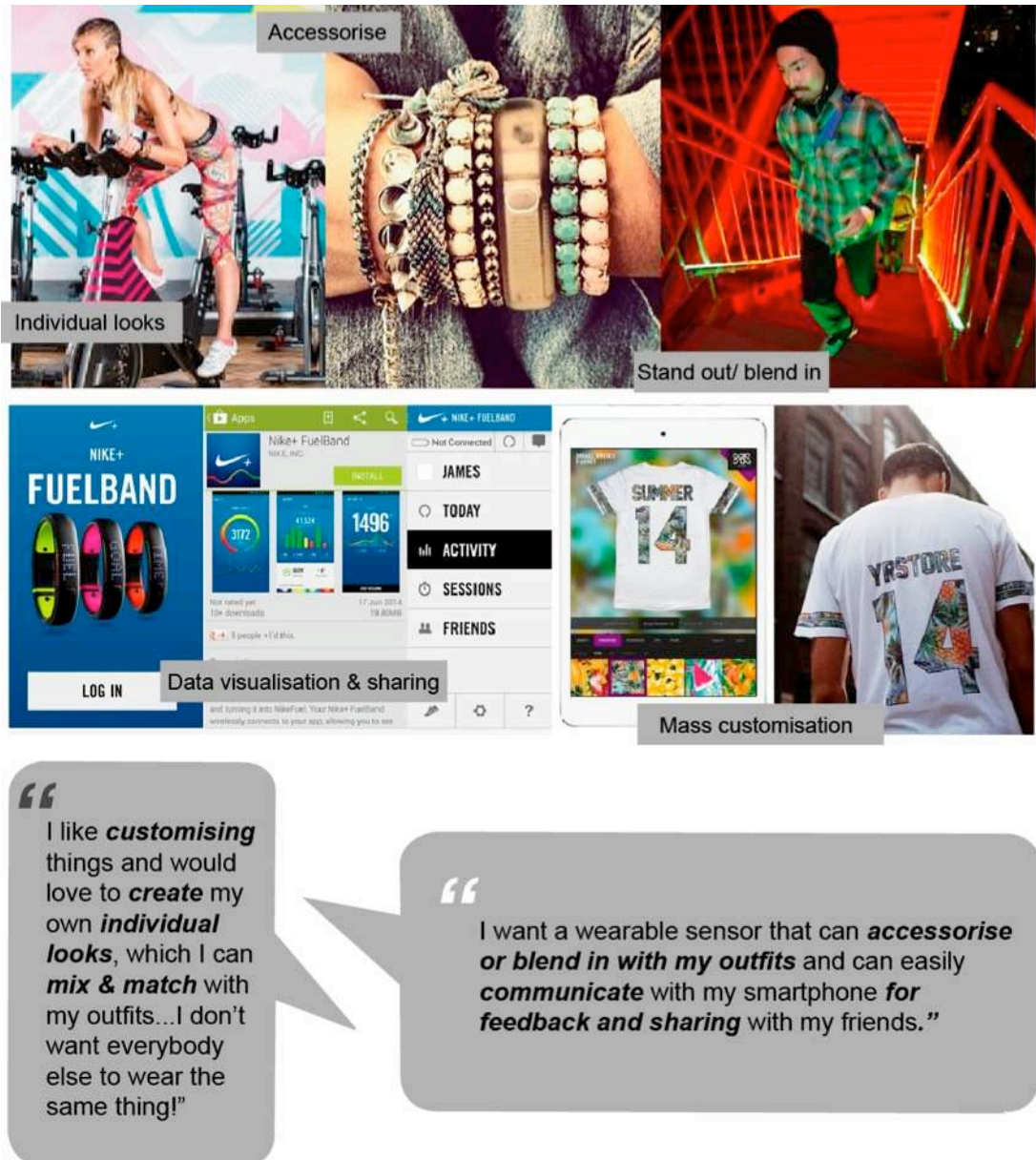


Fig. 9.5: User concept technoista, Prahl (2014): (a) Calgary Avaniso workout look, (b) Nike FuelBand 'arm party', (c) 600 stair climb with FuelBand, (d) YR store customisation app, (e) Nike+FuelBand app

Technoistas (fig. 9.5) are keen to show off their individual taste and look at all times, which can require the wearable sensor to either blend in to a favourite outfit, or stand out as a fashion accessory in its own right. They tend to adopt new technologies after they have been proven useful or cool, love to use the Nike+FuelBand as part of their fitness regime and would like to add wearable sensors to receive more health-specific information. These sensors need to

integrate with their smartphone for feedback and potential data sharing with friends, while they would like to have an input into the design in terms of colour and material.

Techno_DIYer

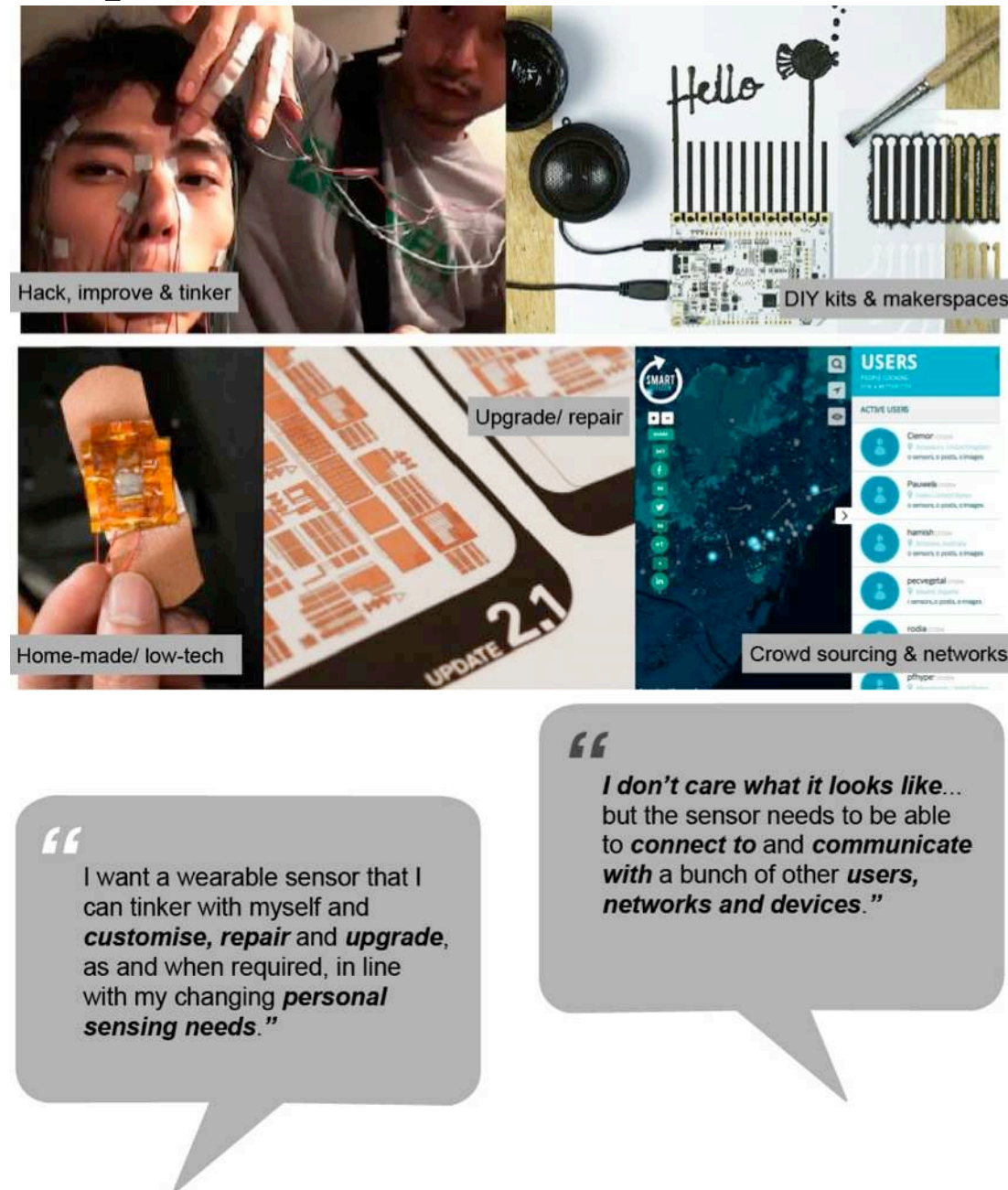


Fig. 9.6: User concept technoDIYer, Prahl (2014): (a) Face-based sensors, (b) Touch Board kit, (c) Smart Citizen user network, (d) customisable electronics, (e) paper-thin sensing plaster

TechnoDIYers (fig. 9.6) consider themselves makers and fixers, who like to hack, change or repair existing or construct new devices and they either create their gadgets from scratch or utilise DIY kits or cutting-edge new technologies, which are available in a rapidly growing number of maker spaces. Although they have tried various self-tracking devices, they soon started hacking into them, in order to add

personalised features and performance. Their creations generally have a homemade or low-tech look about them and they really don't care about aesthetics, as long as the sensing device can connect to other users and networks to contribute to crowd-sourced data.

Techno_SCEPTIC



Fig. 9.7: User concept technosceptic, Prahl (2014): (a) life before Internet, (b) data security, (c) mindful slow tech bracelet, (d) technology addiction illustration

Technosceptics (fig. 9.7) do use smartphones willingly but are aware that it is important to switch off, often considering whether to commit to de-teching their lives, as they are extremely concerned about the potential negative health impacts from using of smartphones, computers and Wearable Technology, both psychological and physical, as well as the issues around data privacy and misuse by companies

or governments. They do however appreciate the concept of wearable sensors in order to protect their health and wellbeing but are looking for a mindful use of sensors, where devices blend in without distracting their daily lives.

Techno_*PHOBE*



Fig. 9.8: User concept technophobe, Prah (2014): (a) low-tech diagnostic device, (b) urine test strip, (c) litmus test, (d) low-tech diagnostic smartphone feedback, (e) low-tech pregnancy diaries

Technophobes (fig. 9.8) have different reasons for avoiding the use of devices in their lives; these can range from simple ignorance about emerging technology to fear or aversion of interacting with devices. With regard to wearable sensors, they might be fearful about wearing electronics close to their bodies or concerned about

having to interact with the device as part of a regular routine and would therefore prefer as little interaction as possible, as data could go directly to a healthcare professional of their choice. *Technophobes* already use analogue tools to keep an eye on their health and wellbeing and are therefore interested in trying new tools, which could provide more accurate and actionable data than simple diary keeping.

9.3 Conclusion

The use of design briefs and creation and application of user profiles to design and develop appropriate products and services are well-established methods in academic and industrial design contexts. However for this project I merged the two methods into one to produce an innovative type of design brief, in order to create the necessary focus and inspiration for the final stage of design practice. These speculative user type concepts provided unique inspiration for myself as a designer, while taking the opportunity to embed key challenges and solutions into the design and development of the wearable sensor collections (chapter 10), so that identified gaps in knowledge can be explored and communicated through the collection of final artefacts.

These user type concepts are speculative and subjective, as they are based on the generation, selection and use of qualitative data in the particular context of my research project. However, as a variety of practice-based methods were utilised to generate the data, the concepts are grounded in diverse and relevant findings and could therefore be used by other designers and researchers to work with, or create their own user type concepts, based on similar methods (chapter 11).

Chapter 10: Wearable sensor collections

In line with the overall proposal of the thesis that wearable sensors should be designed to integrate easily into the user's existing lifestyle, these collections specifically investigate and demonstrate how to bring these types of devices into a lifestyle realm, where they can be worn regularly as part of existing routines and outfits to contribute to long-term improvements to the wearer's health and wellbeing. Furthermore, these collections are designed to embed end-of-life solutions, in order to avoid the creation of a new waste stream by combining electronics and clothing into hybrid products, which could cause significant disposal issues at the end of the device's life.

The new types of wearable devices from sports and medical sectors (i.e. tattoo, plaster and patch-like sensors that can be worn directly on the skin), which have recently emerged (chapter 3), were a significant inspiration for my own design exploration. However, most of these examples are not currently designed with general lifestyle use in mind, where sensors could be worn as part of existing regular routines and everyday situations (i.e. at work, at home, commuting, shopping or socialising). Most of the presented devices were conceived for specific use situations, as various medical sensors are either worn concealed under layers of clothing, or in a hospital or laboratory situation, while sweat sensors developed for athletes, such as temporary tattoos, are worn during specific sporting activities only.

Moreover, these new types of sensors are still in their development phase and would benefit from the involvement of designers who are experienced in the exploration of aesthetics, materials and form; as these particular developments are generally driven by scientists and engineers, they appear to prioritise technical requirements over aesthetic ones. Indeed, during his keynote presentation at Smart Fabrics 2013, Joshua Windmiller, one of the key US based researchers behind epidermal biosensors, conceded that the future success of his science-based developments could greatly benefit from the involvement of a designer to push their aesthetic appeal (Windmiller, 2013). On a similar note, in her blog post on the future of healthcare design, Wearable Technology design expert Jennifer Darmour identified the growing opportunity '*... to blur the boundaries between medical products and lifestyle products*', as she predicted that long-term prevention will

become part of users' daily lives through the use of sensor-enabled tools (Darmour, 2010). Therefore, the creation, presentation and evaluation of these artefact collections aim to contribute transferable knowledge about the design of wearable sensors for Preventative Health in a lifestyle context, which could be utilised by other researchers and designers to create their own research, artefacts, developments or commercial products in the future (chapter 11).

10.1 Artefact collections

These five diverse conceptual collections comprise: a) 'Wearable Skin', b) 'Customise/ Accessorise', c) Make(rs) & fix(ers), d) 'Mindful Measure' and e) 'Bio Sense' and were designed in response to the potential attitudes, needs and preferences of five speculative user types: a) the *technophile*, b) *technoista*, c) *technoDIYer*, d) *technosceptic* and e) *technophobe* respectively. Each collection consists of a concept board, a textile inspiration board, a wearable material swatch board and a colour palette board, which are all presented in this chapter. In addition, concepts constitute a range of design sheets, mock-ups (commercial samples which have been printed on/ mocked-up to illustrate a design) and hand-made samples and swatches.

10.1.1. Wearable Skin

The first collection; *Wearable Skin*, addresses the needs of the *technophile* user and combines their affinity for futuristic approaches and materials by providing wearable sensors that could become a natural extension of the wearer's skin and body, while integrating context-aware, appropriate ways to interact and receive feedback (fig. 10.1). This concept therefore relies on the use of tactile and soft materials, surfaces and forms, in order to support natural interaction with the devices.

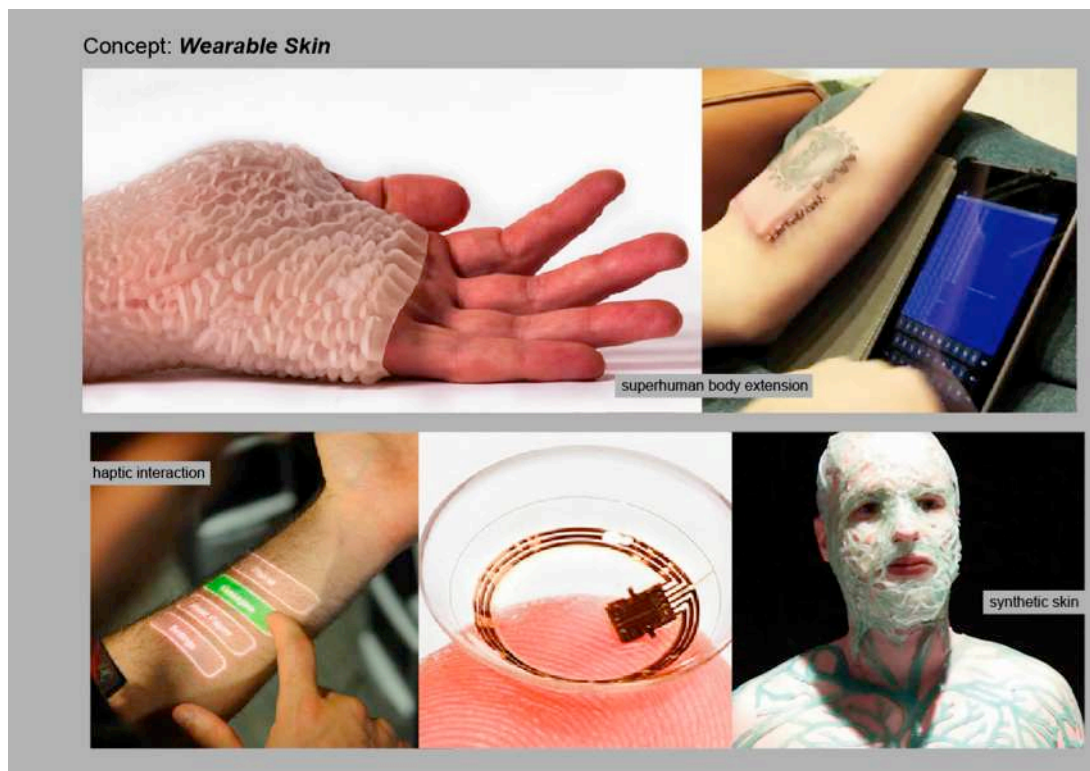


Fig. 10.1: *Wearable Skin* concept board (Prahl, 2014): (a) Skin-like body extension (Neri Oxman), (b) DIY cyborg implant image, (c) synthetic skin extension image, (d) Google smart sensing lens, (e) 'Skinput' interaction system

The textile design aesthetic is inspired by skin-like, soft and tactile surfaces and moulded contours, in combination with sharp, linear printed graphics (fig. 10.2). In particular the sensor substrates in this story explore '*Tech skin*' as a wearable material (fig. 10.3), suggesting the use of soft, synthetic nonwoven rubber-like materials such as synthetic rubber, thermoplastic and silicone, which are comfortable to wear next to the skin, while providing a smooth surface for printing both decorative elements and functional sensing components and circuits.

These types of materials are already utilised for personal healthcare products, such as specialist plasters and covers, gel-like heel and foot pads and foot supports and would be suitable for a range of reusable sensors, as they are durable and washable or wipeable. Many of these are used with medical adhesives, which are discussed in section 10.2.

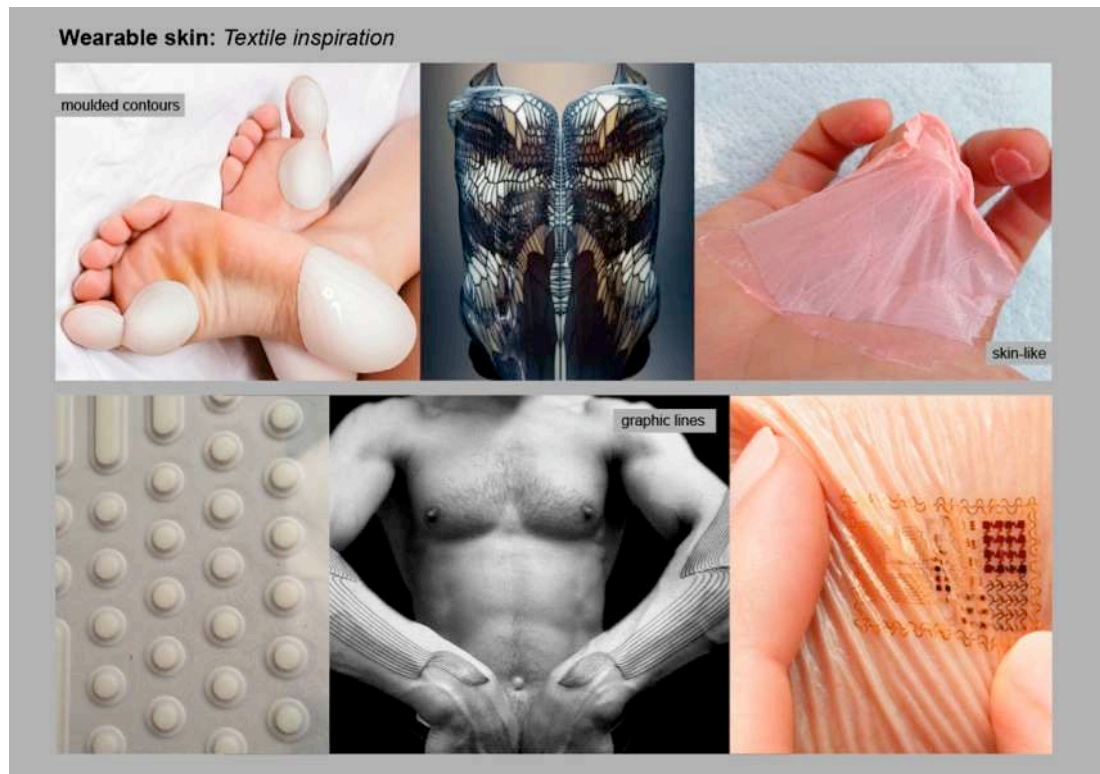


Fig. 10.2: *Wearable Skin* textile inspiration board (Prahl, 2014): (a) flexible second skin (Nike), (b) multi material 3-D printed corset (Neri Oxman), (c) latex paint experiment (Prahl, 2013), (d) electronic skin-based tattoo (MC10), (e) monochrome geometric tattoo (Chaim Machley), (f) internal moulded silicone layer of keyboard

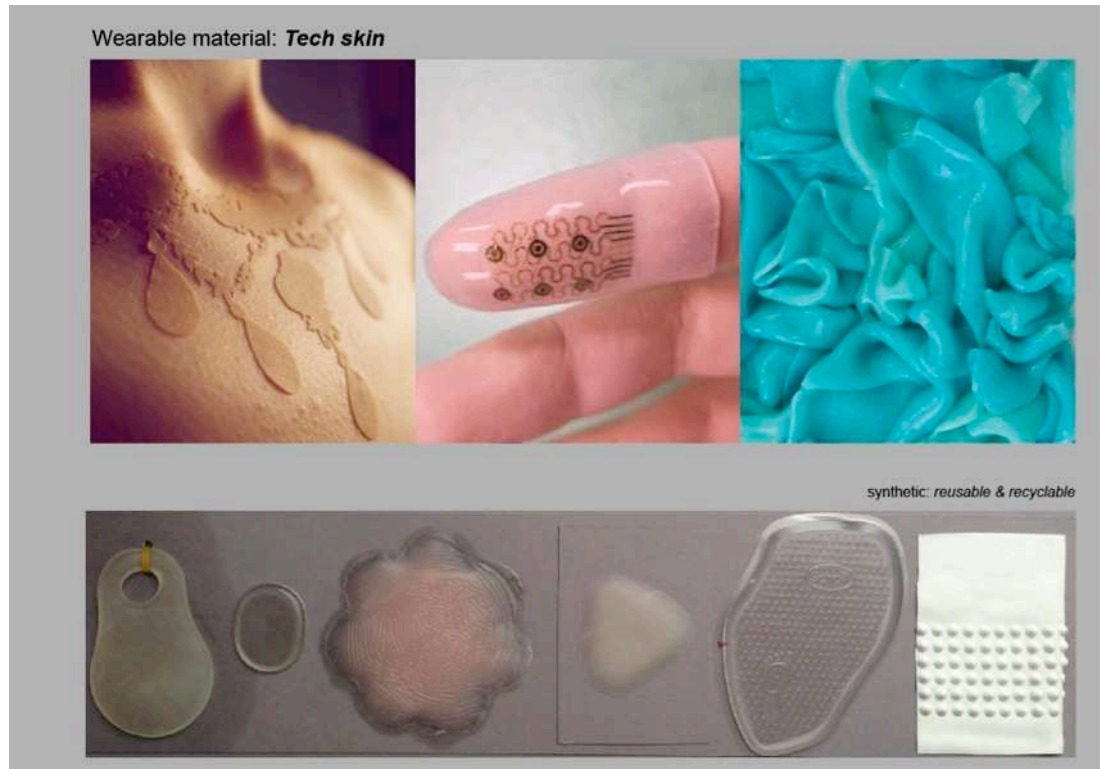


Fig. 10.3: *Wearable Skin* material board 'Tech skin' (Prahl, 2014): (a) skin jewellery (Raluca Grada-Emandi), (b) electronic fingertip (John Rogers), (c) platinum cured silicone rubber (Matthias van Arkel). Commercial samples: thermoplastic elastomer gel, visco-elastic polymer gel, silicone and thermoplastic polyurethane, polyurethane and hydrocolloid gel, visco-elastic polymer gel and synthetic rubber.

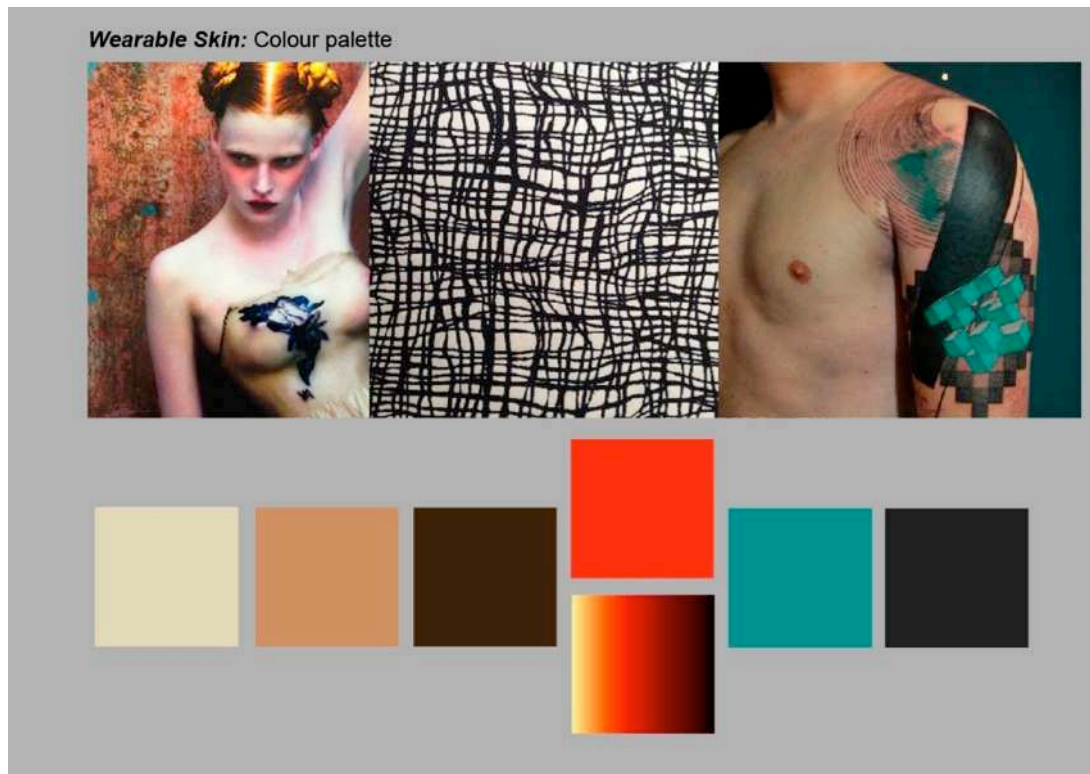


Fig. 10.4: *Wearable Skin* colour palette board (Prahl, 2014), (a) parchment corset by J Smith ESQ, (b) photo of wrapping paper sample, (c) geometric tattoo (Loic Lavenue). Various colour swatches.

The colour palette is based around different types of skin tones, which are contrasted by bold, dark and tattoo-like graphic elements and highlighted with a warm burnt orange, luxurious copper and a vibrant turquoise (fig. 10.4). The four boards were further utilised as an inspiration to design initial ideas for wearable sensing devices, which illustrate how the concept could be interpreted in practice (fig. 10.5-10.7).

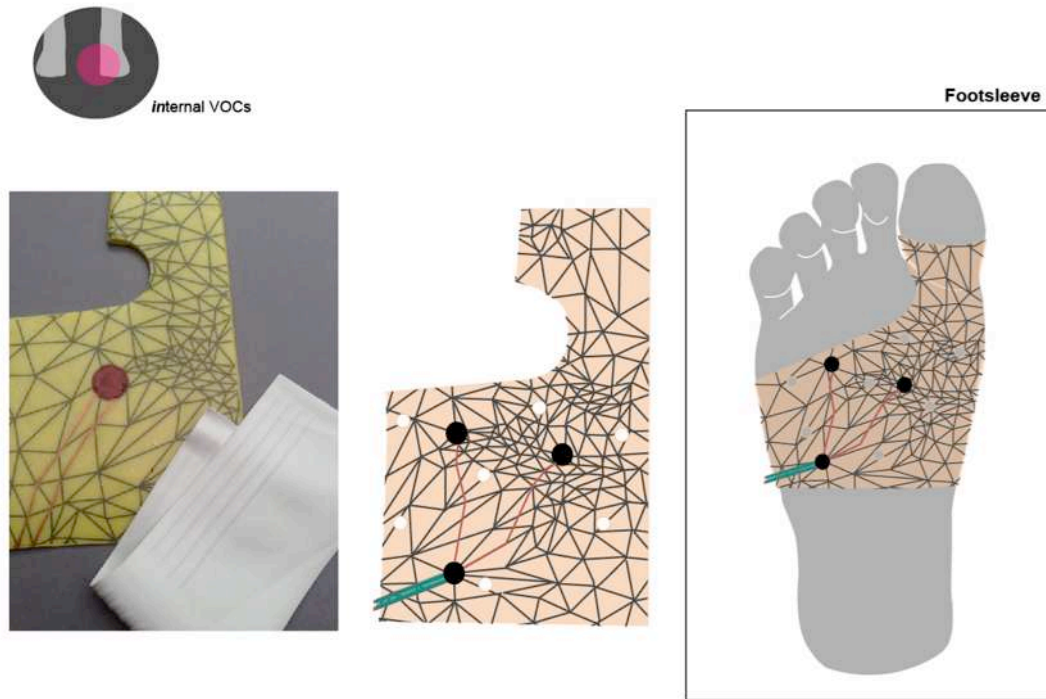


Fig. 10.5: *Wearable Skin* designs and commercial sample mock-ups (Prahl, 2014)

Designs and samples include a foot sleeve (fig. 10.5), forearm sleeve (fig. 10.6) and foot and forearm adhesive patches (fig. 10.7).

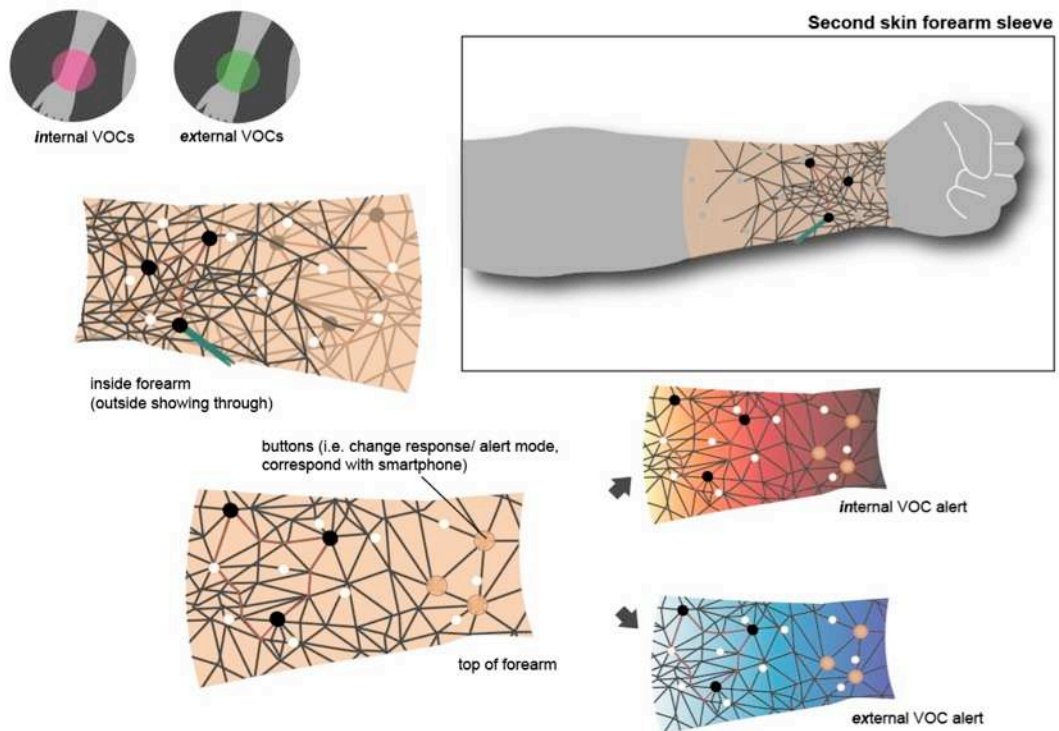


Fig. 10.6: *Wearable Skin* designs (Prahl, 2014)



Fig. 10.7: *Wearable Skin* commercial sample mock-ups (Prahl, 2014)

For this collection, the focus was on sensing both internal and external VOCs, which could be worn in combination with other types of sensors, in order to generate a more holistic and complete overview of the wearer's health. The wearer could choose to receive initial alerts either through the device itself or their smartphone, while the data can be combined with data from other sensors, devices and apps, in order to merge the data to allow the user to act based on information received through their smartphone or a healthcare professional (fig. 10.8).

SENSOR ECOSYSTEM:

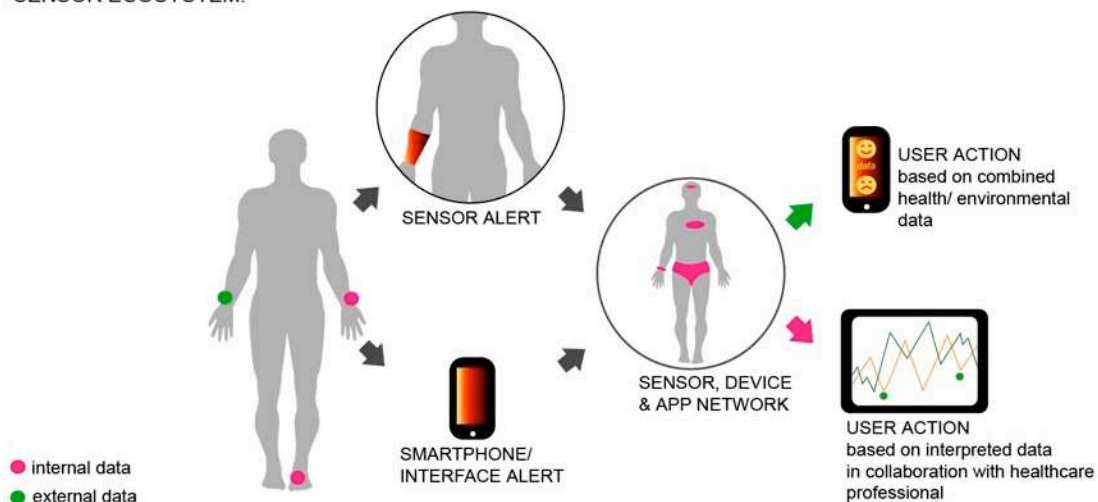


Fig. 10.8: *Wearable Skin* sensor ecosystem diagram (Prahl, 2014)

10.1.2 Customise/ Accessorise

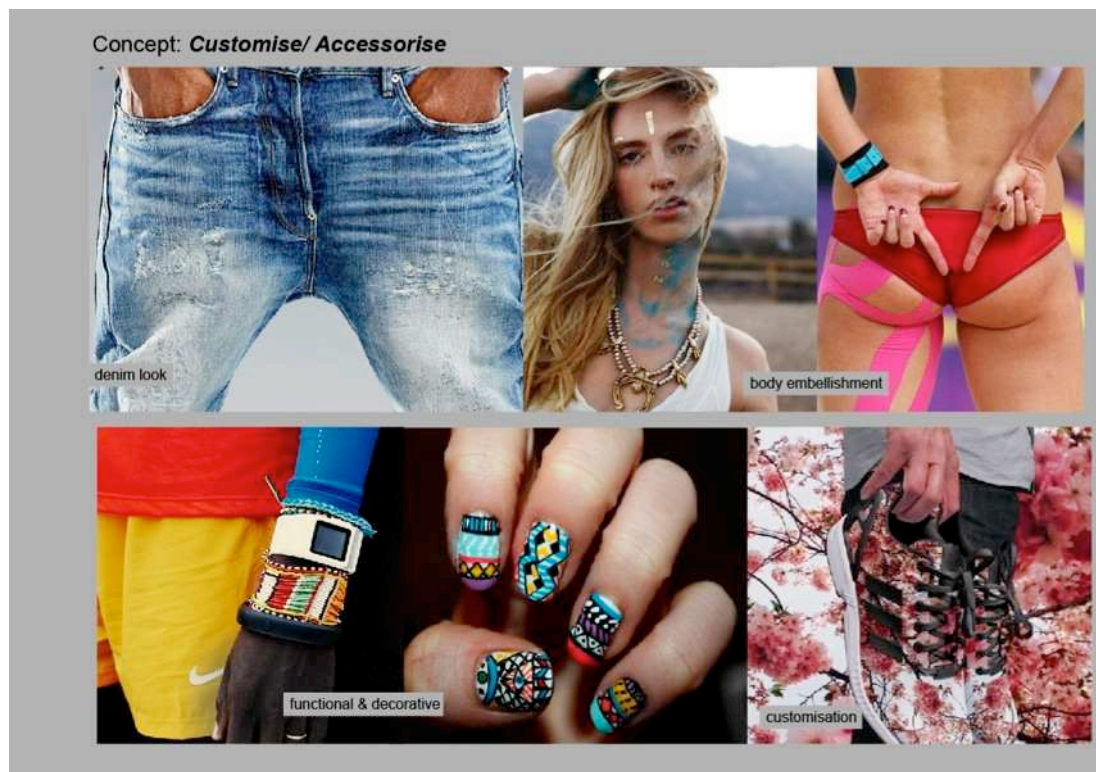


Fig. 10.9: *Customise/ Accessorise* concept board (Prah, 2014): (a) worn-in jeans (G-Star), (b) golden beauty marks (Mr. Kate), (c) Olympic athlete tape image, (d) customised printing (adidas), (e) decorative nail wraps, (f) accessorised wrist (Nike).

The second collection; *Customise/ Accessorise* responds to the *technoista's* need for wearable sensors that can either blend into and complement an existing outfit or stand out as accessories in their own right. This can be achieved by choosing from a range of denim shades or customised graphic elements, which are both functional and decorative (fig. 10.9). The user would first select a suitable design silhouette for the desired on-body location and data to be sensed, before choosing a substrate material and colourway. In order to take customisation even further, they could also upload their own artwork or photographs to be printed on the sensor substrate, thus creating an entirely personal look.

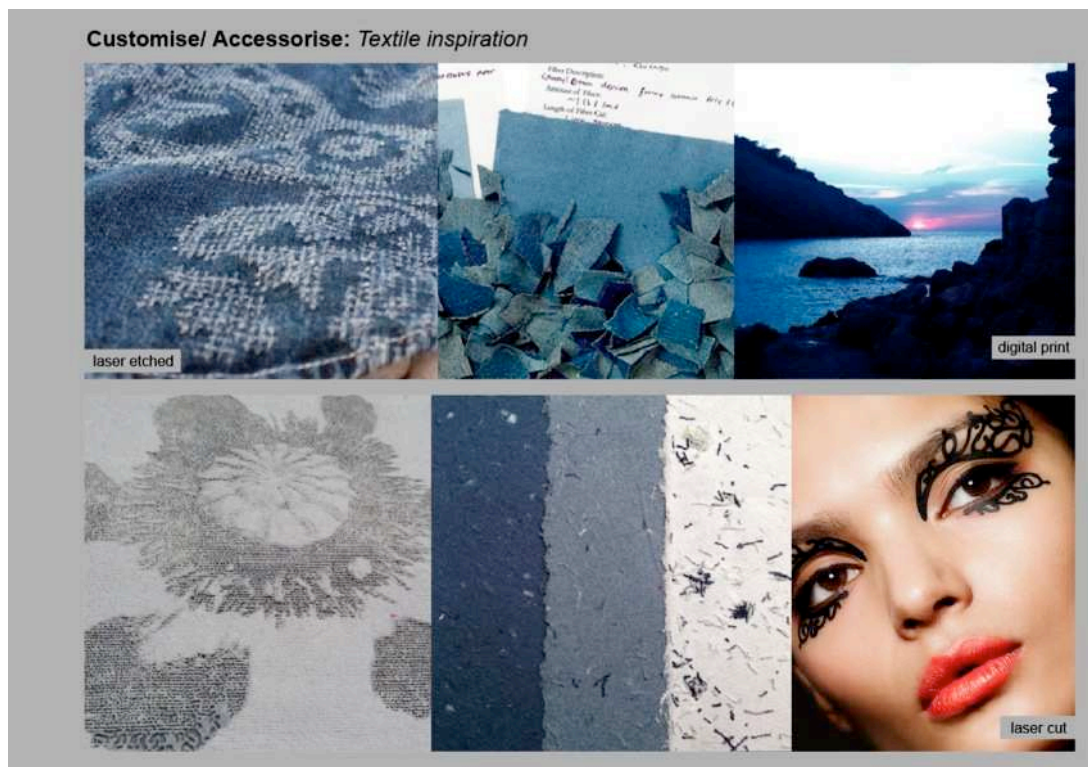


Fig. 10.10: *Customise/ Accessorise* textile inspiration board (Prahl, 2014): (a) laser-etched denim (jeanologia), (b) paper-based denim, (c) holiday photo digital print (Prahl, 2014), (d) laser-cut 'face lace' (Phyllis Cohen), (e) hand-made denim paper samples (Prahl, 2014), (f) laser-etched Tyvek sample (Prahl, 2009)

The textile design aesthetic is based on laser-etched and laser-cut surfaces, various shades and compositions of denim-like materials and digital print (fig. 10.10). This story explores 'Tech paper' as a wearable material, investigating synthetic nonwoven paper-like materials such as Tyvek (100% Polyethylene), Evolon (Polyester, Polyamide and water) and Polypropylene and Polyester (fig. 10.11). Although these materials are relatively rigid, they could be suitable for the design of fabric-like reusable tattoos, by utilising laser-cut patterns to create extra breathability and flexibility and they also make an excellent base for the application of decorative and functional printing. Due to the materials' strength, durability and wipeability, sensors could be designed to be reusable for a specific period of time. Examples of how these types of materials are already used on and around the body include disposable underwear, adhesive bras and fabric-like plasters. The colour palette (fig. 10.12) combines five shades of denim, ranging from white to dark indigo, which are complemented by bright lime, orange, turquoise and mint highlights.

Wearable material: **Tech paper**

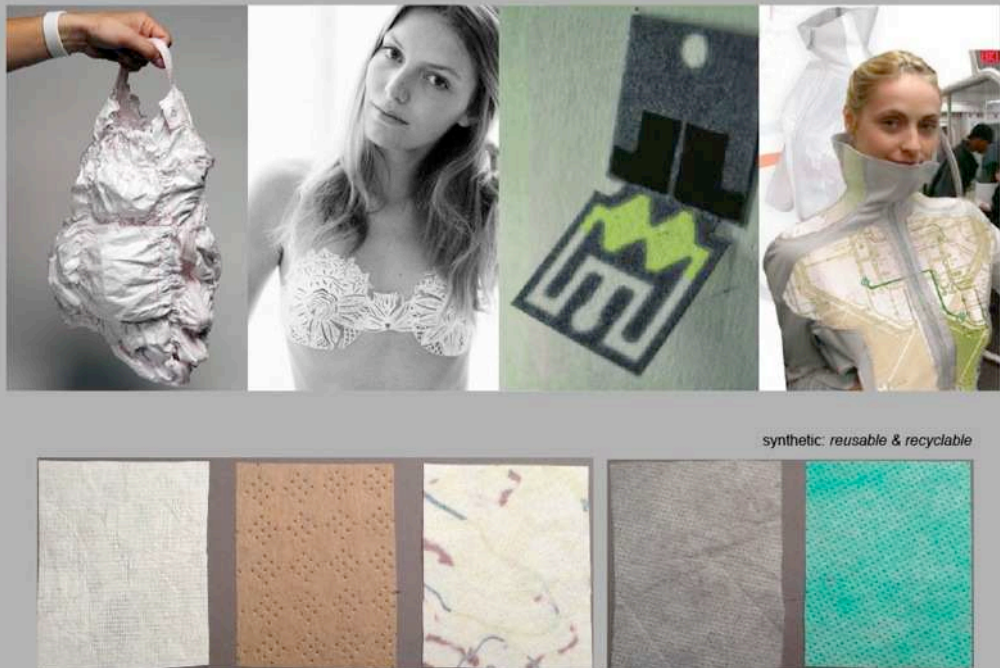


Fig. 10.11: *Customise/ Accessorise* material board 'Tech paper' (Prahl, 2014): (a) Tyvek bag (Lily Jacobs), (b) paper bra (Bodil Jane Kleipool), (c) paper-based sensor (Hong Liu) (d) e-paper jacket (Lunar Design), (e) commercial samples including Tyvek, Polyester, Evolon and Polypropylene (x2)

Customise/ Accessorise: Colour palette



Fig. 10.12: *Customise/ Accessorise* colour palette board (Prahl, 2014): (a) denim letters magazine cover (Sportswear International), (b) customised and accessorised backpack (Chanel), (c) photograph of recycled magazines strips for papermaking (Prahl, 2014), (d) various colour swatches.

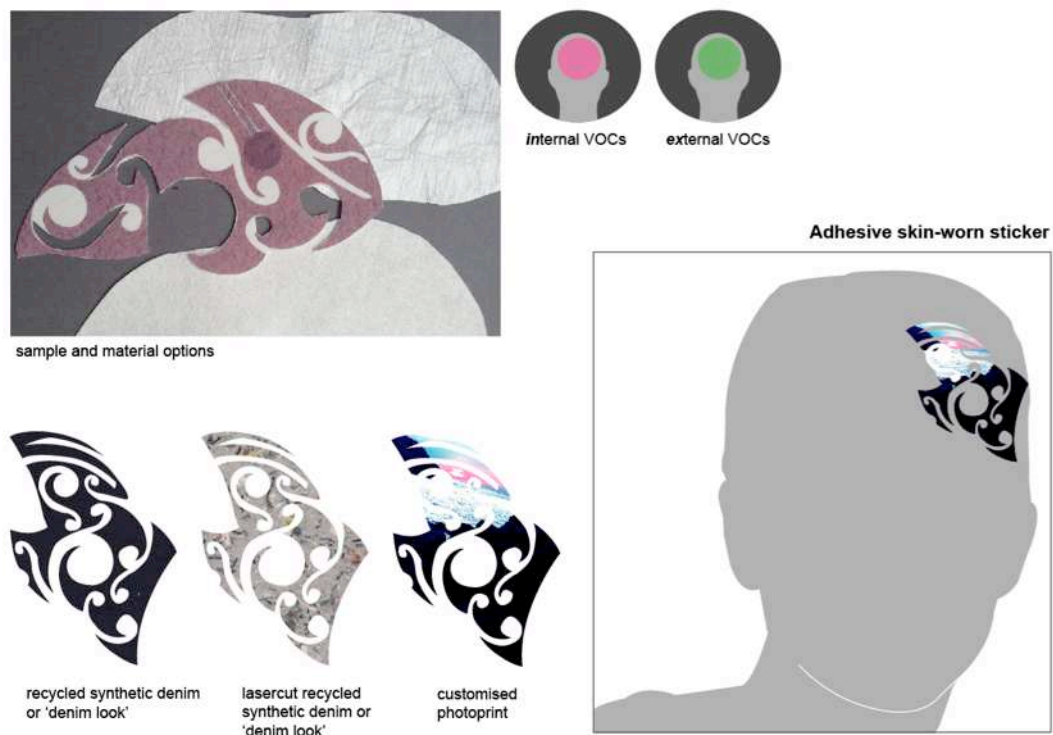


Fig. 10.13: *Customise/ Accessorise* designs, hand-made samples & swatches (Prahl, 2014)

Designs and samples include adhesive skin-worn stickers (fig. 10.13 and 10.14) and stickers that can be worn on the skin or attached to the outside of clothing (fig. 10.15).

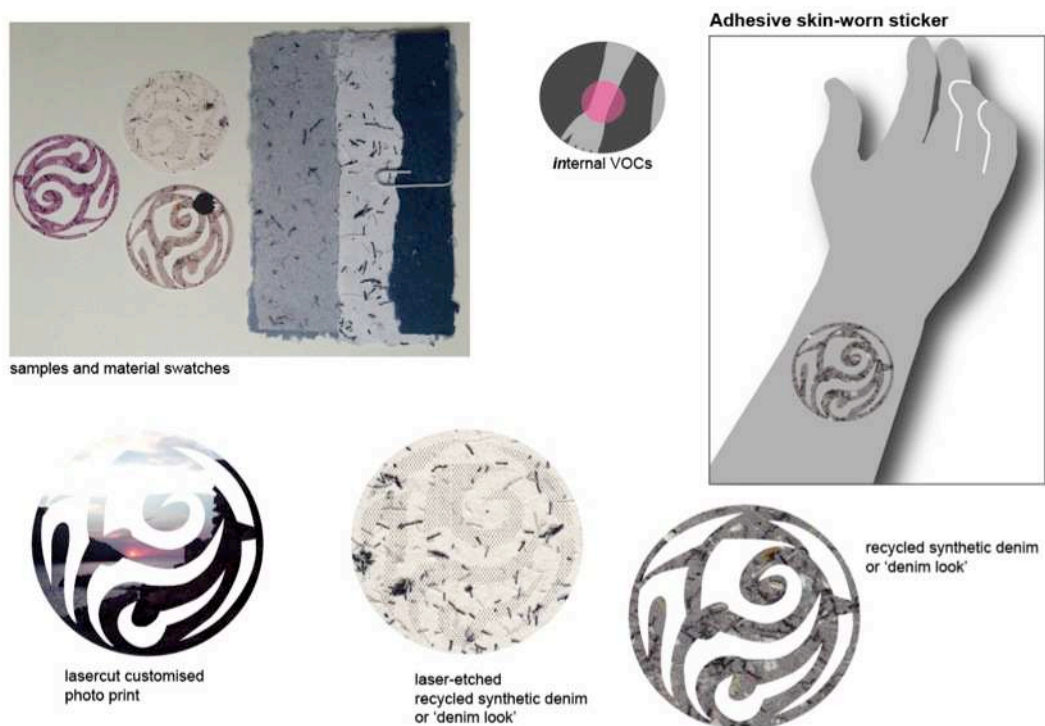


Fig. 10.14: *Customise/ Accessorise* designs, hand-made samples & swatches (Prahl, 2014)



Fig. 10.15: *Customise/ Accessorise* skin and clothing attachable design, hand-made sticker samples (Prahl, 2014) and commercial samples

SENSOR ECOSYSTEM:

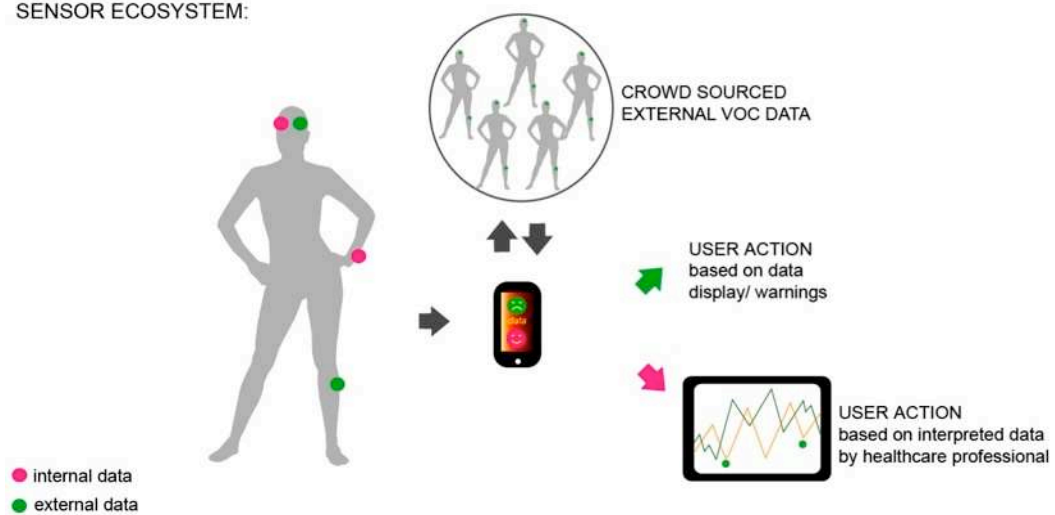


Fig. 10.16: *Customise/ Accessorise* sensor ecosystem diagram (Prahl, 2014)

This collection considers both internal and external VOC sensing, and the external (environmental) data can be linked to other users' data to provide more complete reading of environmental pollution, on which the user may wish to act based on smartphone alerts, while internal data is interpreted by a healthcare professional (fig. 10.16).

10.1.3 Make(rs) & fix(ers)

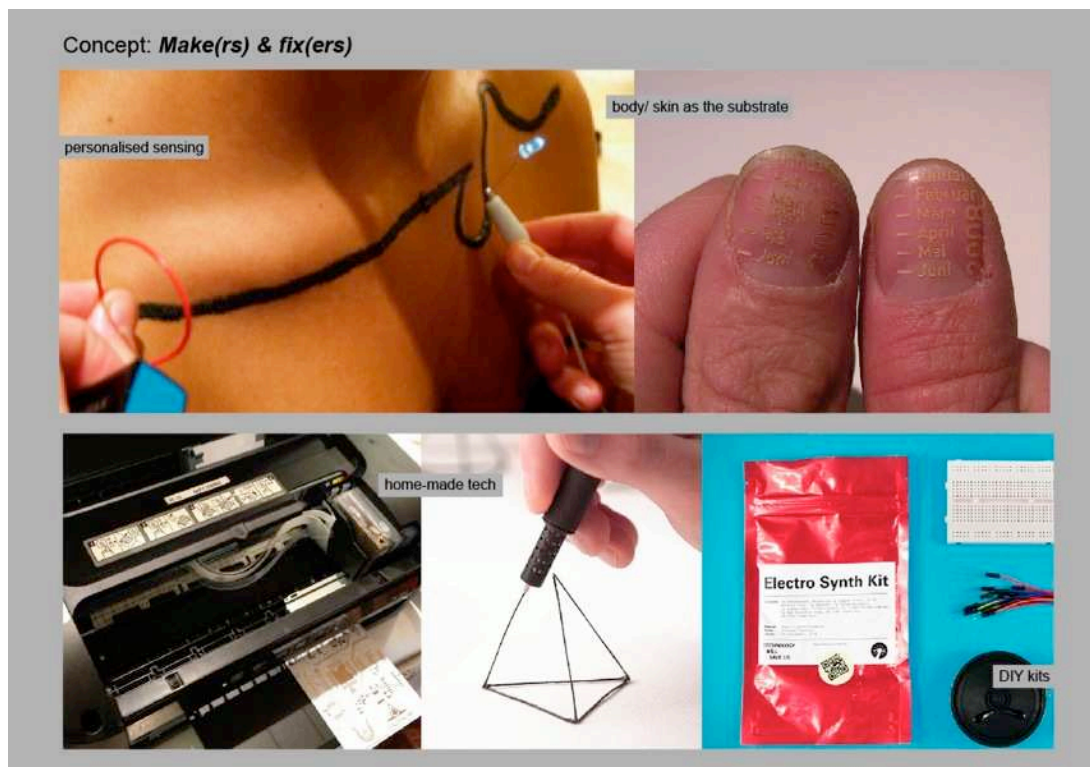


Fig. 10.17: *Make(rs) & fix(ers)* concept board (Prahl, 2014): (a) skin-based conductive ink (Bare Conductive), (b) engraved nails, (c) electro DIY kit (Technology Will Save Us), (d) 3-D printing pen (Lix), (e) inkjet printed conductive circuits (Colloidal Ink)

The third collection; *Make(rs) & fix(ers)*, addresses the technoDIYer's desire to get involved in the creation of the devices themselves by considering opportunities for personalised sensing, using the body and skin as a 'material substrate' and employing DIY kits and home-made tech such as 3-D printing pens and conductive printing through conventional inkjet printers (fig. 10.17). This concept takes into account three different options for the creation of wearable sensors; firstly, the use of sensing kits, which would consist of pre-determined adhesive substrate shapes and sizes in line with desired on-body location/ stimuli to be sensed and connectors to other devices and conductive elements, so that the user can customise and assemble the elements based on their requirements. Secondly, the user could print substrates and sensing elements at home or in a maker space, and apply a printed sensing tattoo to the surface, adding other elements such as LEDs, conductive body paint and batteries in line with their requirements for function and feedback. Thirdly, the user could simply paint the desired colour, size and shape of latex directly on the skin and apply a customised and self-printed sensing tattoo to the surface and further enhance the sensors' functionality by adding conductive body paint, batteries and LEDs, in order to customise functionality and alert and feedback options.

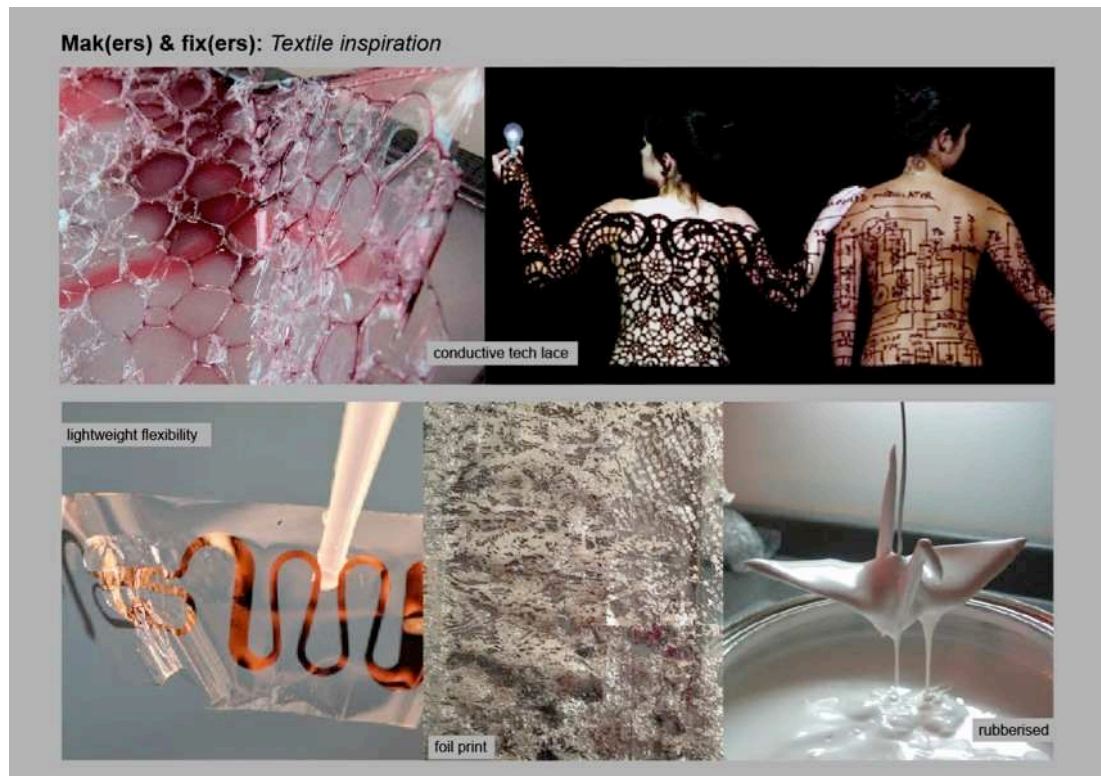


Fig. 10.18: *Make(rs) & fix(ers)* textile inspiration board (Prahl, 2014): (a) bioplastic textures image, (b) conductive body paint (Bare Conductive), (c) rubber dipped paper image, (d) silver foil print on plastic (Prahl, 2011), (e) bioplastic electronics (John Rogers)

The textile design aesthetic is inspired by decorative and functional conductive lace patterns, which are combined with silver foil prints on soft rubberised surfaces and lightweight flexible substrates (fig. 10.18). In particular, the sensor substrates in this story explore the concept of 'Bio film' as a wearable material (fig. 10.19) by utilising transparent and coloured liquid natural rubber to create the sensor substrates, which include customised plaster-like shapes with both smooth and embossed surfaces. The samples created as part of this concept are thin, comfortable and flexible next-to-skin substrates, which are suitable for printing with both decorative and functional elements. Depending on the thickness and making of the substrate (moulded or painted directly on the body), they can be designed to be more durable and reusable for several wears, or disposable (biodegradable or recyclable) after one wear.

The colour palette (fig. 10.20) consists of muted blue, light and dark greys and light and dark greens, which are contrasted by acid yellow and sky blue highlights and silver and gold print colours.

Wearable material: **Bio film**



Fig. 10.19: *Make(rs) & fix(ers)* material board 'Bio film' (Prahl, 2014): (a) stretchable plastic electronics (Nokia), (b) ornamental rubber clothing (Andreea Mandrescu), (c) sprayable clothing (Fabrican), (d) hand-made swatches: latex rubber (x2), latex rubber and paper, bioplastic and flock, latex rubber and commercial sample (breathable film plaster)

***Make(rs) & fix(ers)*: Colour palette**



Fig. 10.20: *Make(rs) & fix(ers)* colour palette board (Prahl, 2014): (a) Bright highlights (Hua Jia), (b) metallic shades with acid highlight (Technology Will Save Us), (c) muted darks with acid highlight (Hartman Fine Art), (d) various colour swatches

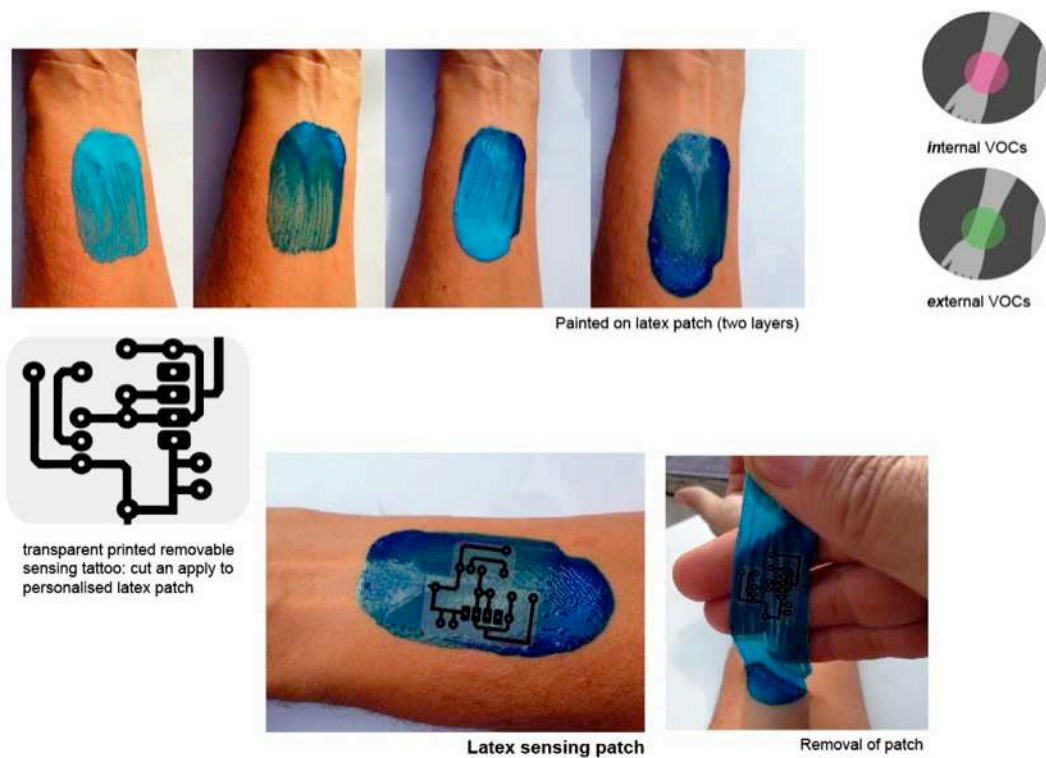


Fig. 10.21: *Make(rs)* & *fix(ers)* designs and hand-made samples (Prahl, 2014)

Designs and samples include painted latex sensors (fig. 10.21) and adhesive sensing plasters (fig. 10.22), which could be customised and connected to various other elements (fig. 10.23).

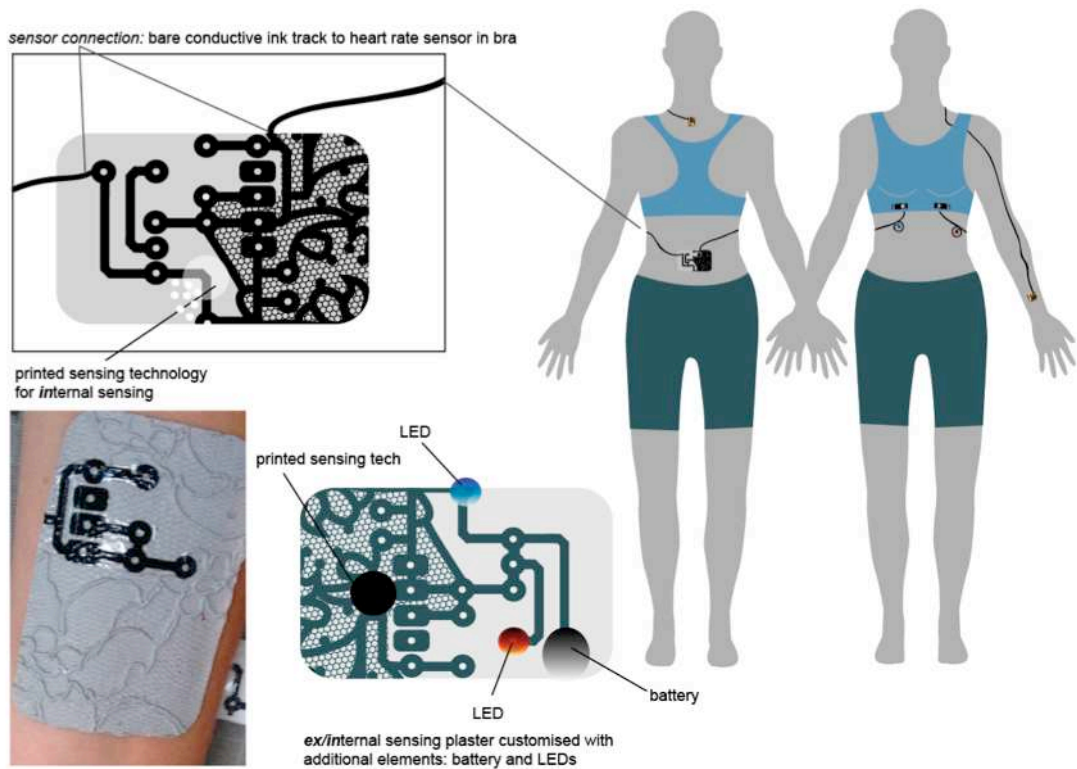


Fig. 10.22: *Make(rs)* & *fix(ers)* designs and hand-made samples (Prahl, 2014)



Fig. 10.23: *Make(rs)* & *fix(ers)* hand-made rubber samples (Prahl, 2014)

SENSOR ECOSYSTEM:

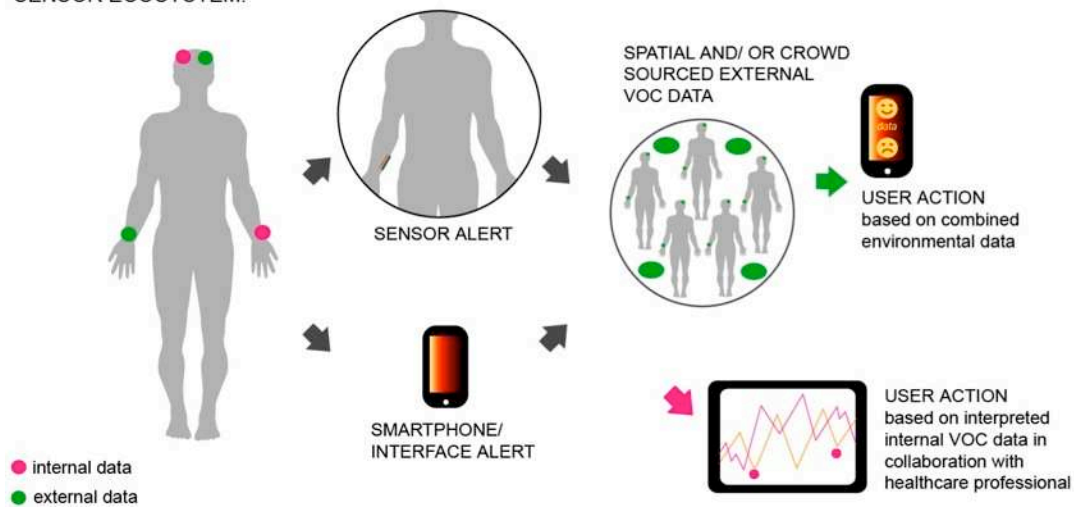


Fig. 10.24: *Make(rs)* & *fix(ers)* sensor ecosystem diagram (Prahl, 2014)

This collection focuses on sensing internal and external VOCs from the wearer and the environment. Initial alerts in response to internal and external data can be given through the wearable sensor itself or a smartphone, and while internal data is then communicated to a healthcare professional in order to determine user action, external data can be linked up with both spatial/ environmental sensors and crowd-sourced data, to provide a more accurate view of environmental pollution, in order for the wearer to take action (fig. 10.24).

10.1.4 Mindful Measure

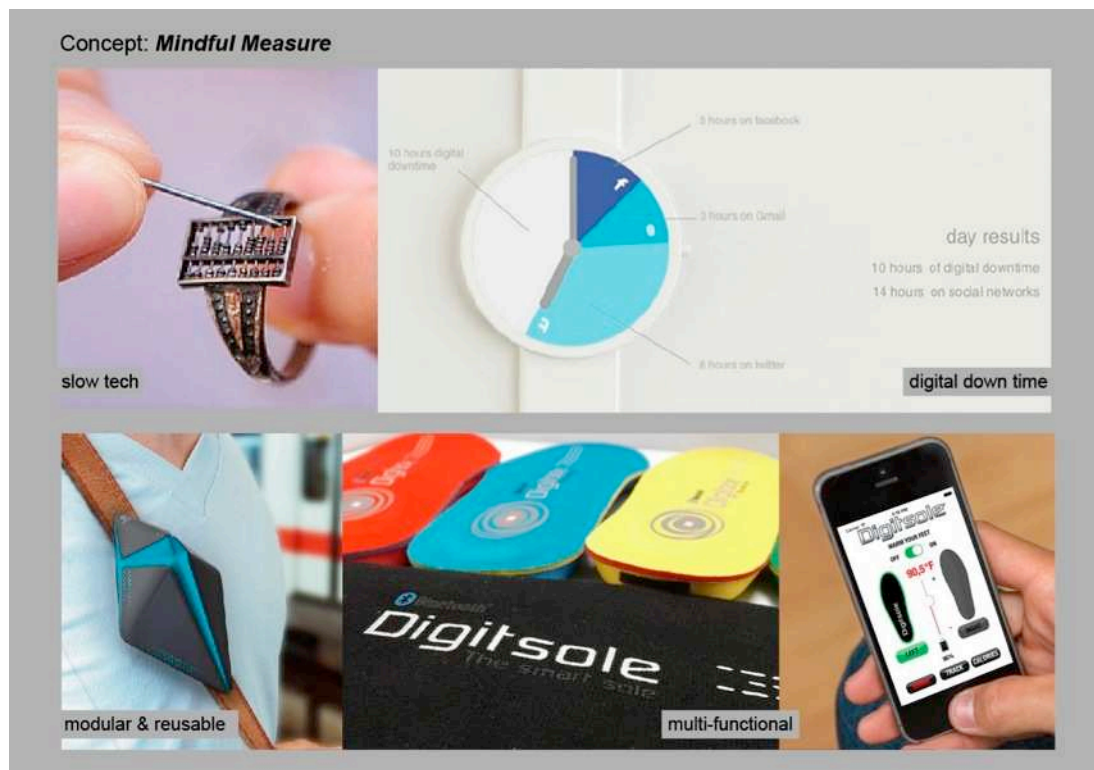


Fig. 10.25: *Mindful Measure* concept board (Prahl, 2014): (a) abacus ring image, (b) digital down time clock (Hector Serrano), (c) Digitsole sensor and heater insole and app, (d) portable air filter (Jorge Alberto Treviño Blanco)

The fourth collection; *Mindful Measure*, responds to the needs of the technosceptic, and addresses their desire for a more mindful use of wearable sensors by allowing for digital down time and a slow-tech approach. Devices are multi-functional, modular, durable and removable, making reusability a key feature (fig. 10.25).

The textile design aesthetic is inspired by contrasting materials and provides a particularly tactile and warm to touch story including natural fibre in rubber encapsulation, natural fibre and rubber-bonded contrasts and rubber-coated felt, while rubber mesh and embossed textures provide ventilation or grip as required (fig. 10.26).

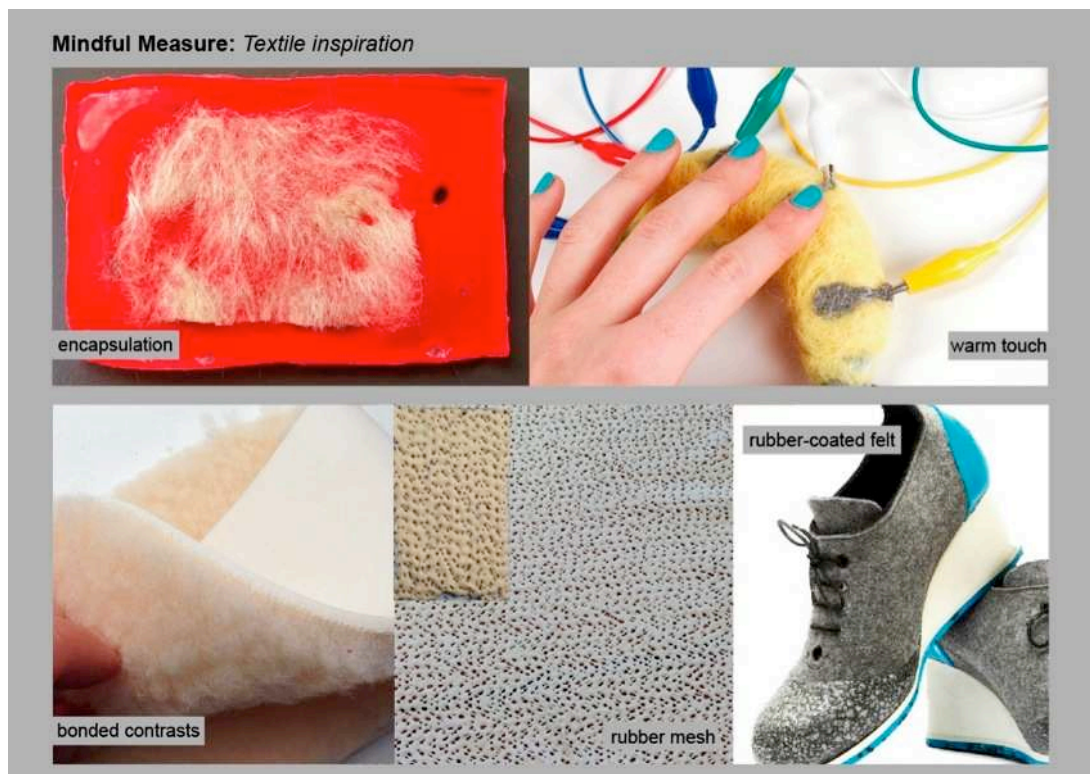
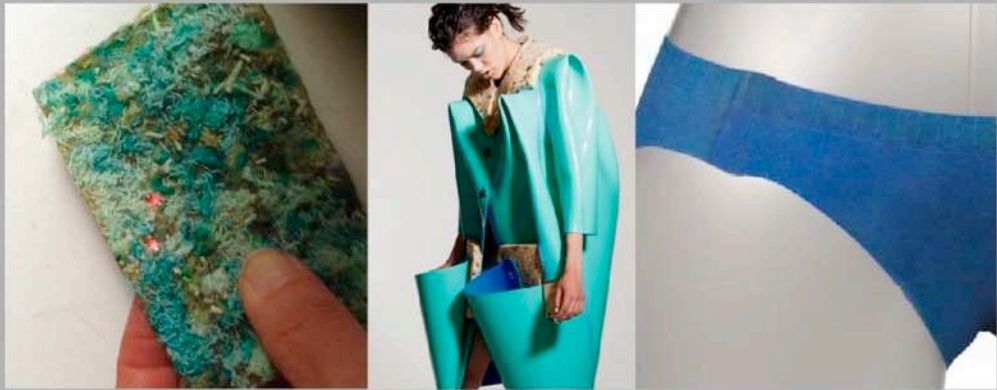


Fig. 10.26: *Mindful Measure* textile inspiration board (Prahl, 2014): (a) hand-made rubber encapsulated natural fibre sample (Prahl, 2014), (b) needle felted touch sensor (adafruit), (c) rubber coated felt (Woolings Shoes), (d) rubber mesh sample (Tamicare), (e) rubber/ felt bonded insole sample (Scholl)

This collection scrutinises ‘*Bio-tech felt*’ as a wearable material for sensor substrates, utilising felt-like substrates, such as pre-made natural and synthetic felt, as well as hand-made, needle-felted materials (fig. 10.27). Felt has the advantage of being soft and tactile but is unsuitable for direct printing with enabling or supporting technologies, due to its hairy surface, so the design and sample-making approach combined felt with a thin layer of natural rubber, in order to provide features that a 100% felt-based substrate could not. Therefore, a thin, natural rubber print was applied to samples in order to provide a smoother surface to achieve a more suitable base for printing, while other samples, such as adhesive footpads and insoles were given a natural rubber backing to add durability and non-slip features. Most of the sensors in this collection could be reusable over a longer period of time, and depending on whether they are made from synthetic or natural components, would be recyclable or biodegradable.

The colour palette (fig. 10. 28) consists of muted darks, including olive, brown and grey, in combination ecru, which are highlighted with vibrant light blue and bright ochre.

Wearable material: **Bio-tech felt**



natural or biosynthetic: *biodegradable and/ or recyclable*



Fig. 10.27: *Mindful Measure* material board 'Bio-tech felt' (Prahl, 2014): (a) hand-made rubber and flock sensor sample (Prahl, 2014), (b) rubber-coated felt clothing (Valeska Jasso Collado), (c) latex and cotton printed underwear (Tamicare), (d) bought samples: felt and rubber insole, adhesive felt patch, felt and rubber insole, rubber cotton printed underwear, hand-made rubber and flock sample (Prahl, 2014)

Mindful Measure: Colour palette

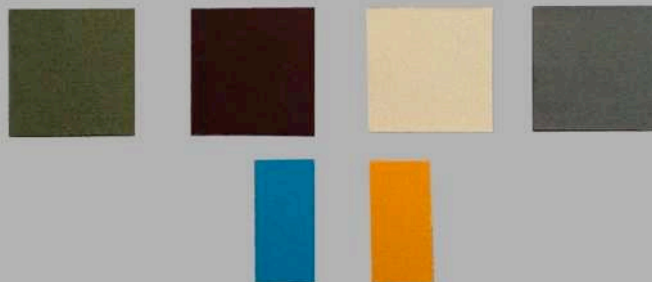


Fig. 10.28: *Mindful Measure* colour palette board (Prahl, 2014): (a) moss-like felt sensor (Andrea Miller), (b) painted wood (Nathan Craven), (c) hand-made latex and bamboo sample (Prahl, 2013)

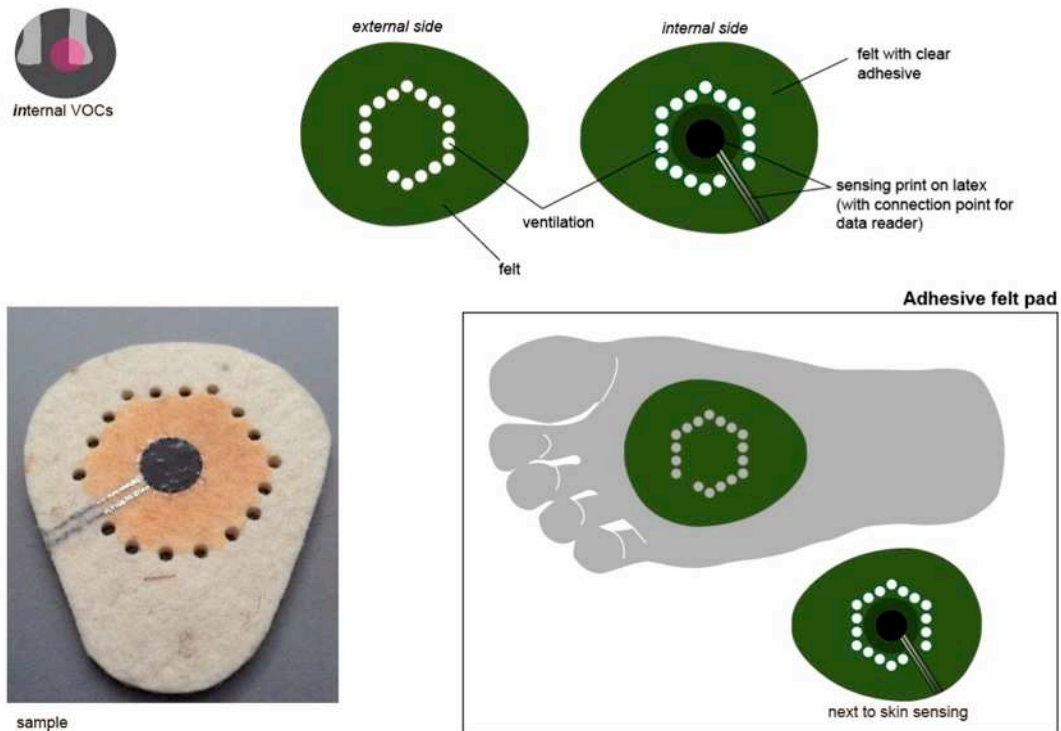


Fig. 10.29: *Mindful Measure* designs and hand-made sample (Prahl, 2014)

Designs and samples include adhesive footpads (fig. 10.29, 10.30), insoles (fig. 10.30) and adhesive felt and rubber pads worn attached to clothing or accessories (fig. 10.31).

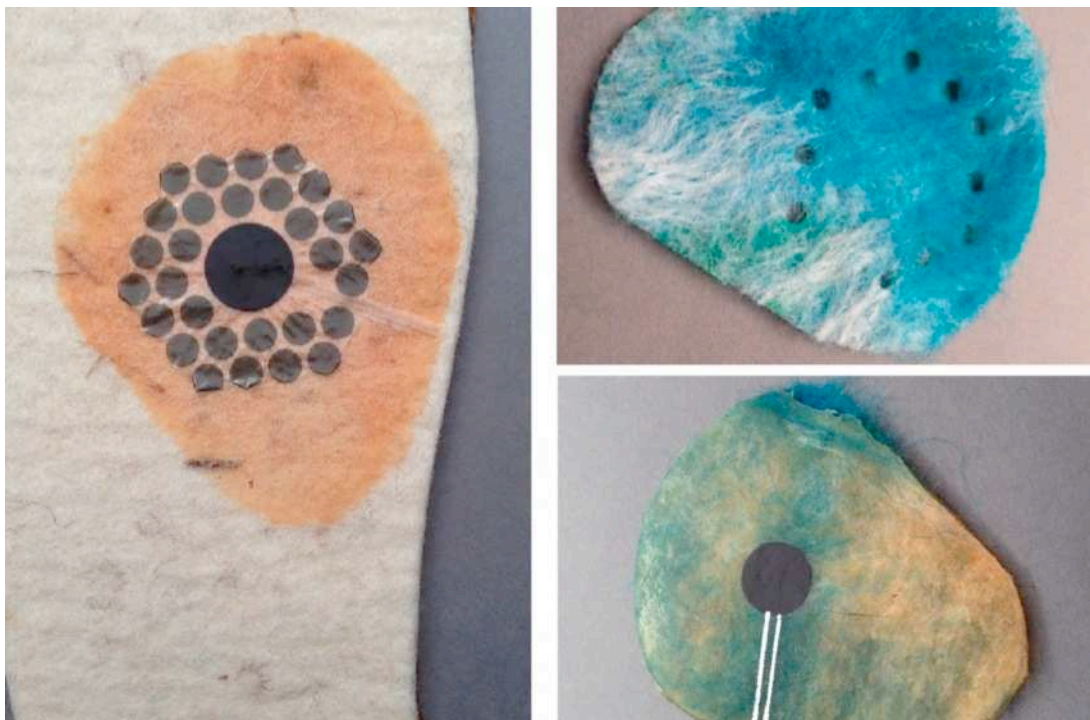


Fig. 10.30: *Mindful Measure* hand-made samples (Prahl, 2014)

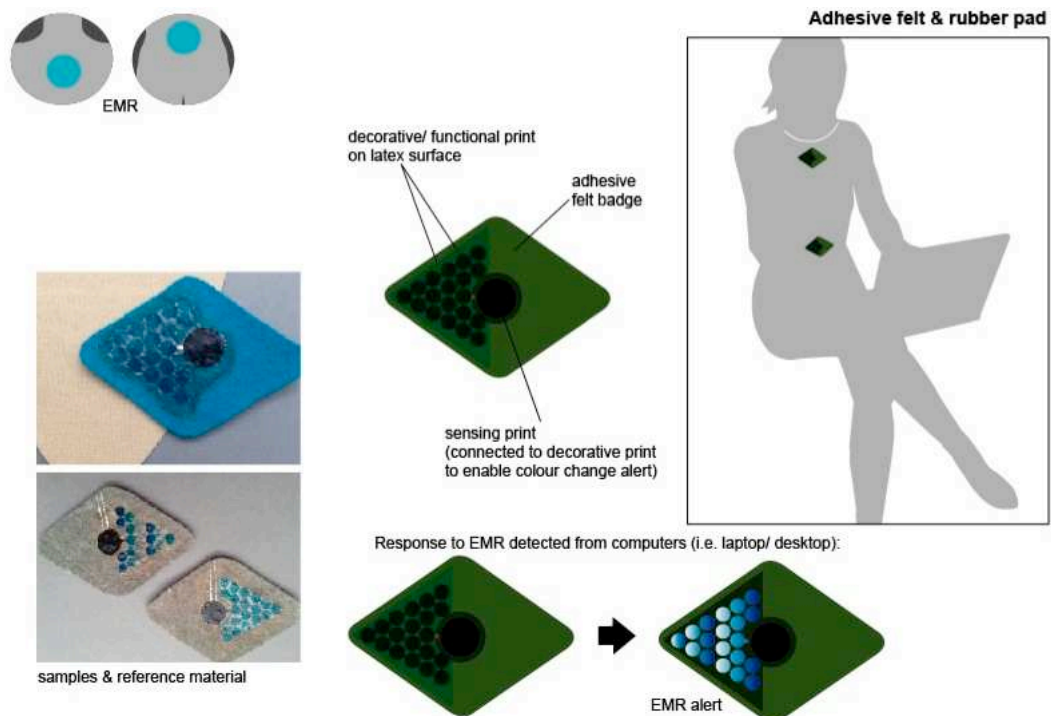


Fig. 10.31: *Mindful Measure* designs and hand-made samples (Prahl, 2014)

SENSOR ECOSYSTEM:

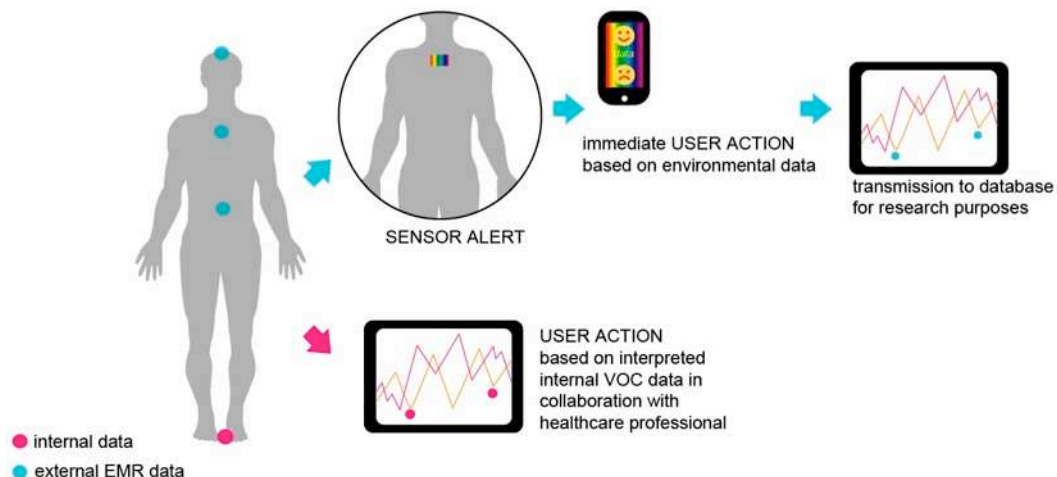


Fig. 10.32: *Mindful Measure* sensor ecosystem diagram (Prahl, 2014)

This collection focused on providing wearable sensing for internal VOCs or external EMR data (fig. 10.32). As the *technosceptic* is concerned about distraction by unnecessary data visuals and the possibility of becoming obsessed with checking internal VOC data, this data goes directly to a healthcare professional to interpret, in order for the user to act appropriately, while alerts on external EMR data are provided either through the sensor itself or the smartphone, so the user can take the necessary action immediately. EMR data is also passed on to a database for research purposes, as this field is in need of gathering more scientific evidence.

10.1.5 Bio Sense

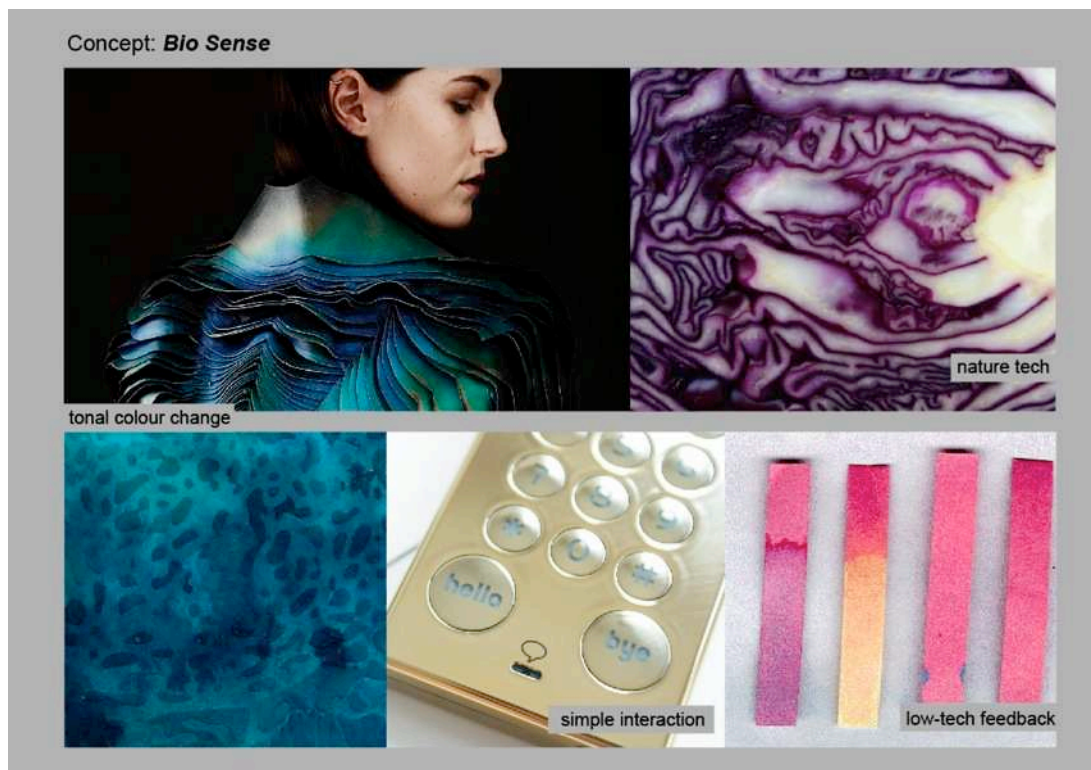


Fig. 10.33: *Bio Sense* concept board (Prahl, 2014): (a) stimuli responsive clothes (The Unseen), (b) red cabbage close-up photo (Prahl, 2014), (c) litmus test strips image, (d) low-tech mobile phone image, (e) thermochromic flock (Prahl, 2009)

The final collection *Bio Sense* (fig. 10.33) responds to the needs of the *technophobe*, who craves simple interaction and low-tech colour-coded feedback, preferably without the need for on-body electronics. The textile design aesthetic is inspired by stimuli-responsive colour change and perforated and embossed, lightly textured patterns. This collection explores 'Bio paper' as a wearable material (fig. 10.34), probing the design and making of natural and semi-synthetic paper substrates, inspired by various types of low-tech paper and paper-like materials used in the medical & beauty industry (fig. 10.35), including facial blotting paper, litmus paper, Frownies adhesive paper patches used to correct wrinkles) and adhesive medical tape (100% viscose). Samples were created utilising embossing, perforation and colour responsive techniques, including thermochromic pigment and cabbage dye. Due to the materials used and their lack of durability, these types of sensors could be designed to be disposable (biodegradable or recyclable).



Fig. 10.34: *Bio Sense* textile inspiration board (Prahl, 2014): (a) thermochromic textiles (Hypercolor), (b) embossed paper pattern hand-made sample (Prahl, 2014), (c) stimuli-responsive textiles (Dahea Sun), (d) perforated paper image, (e) thermochromic print (Kerri Wallace)

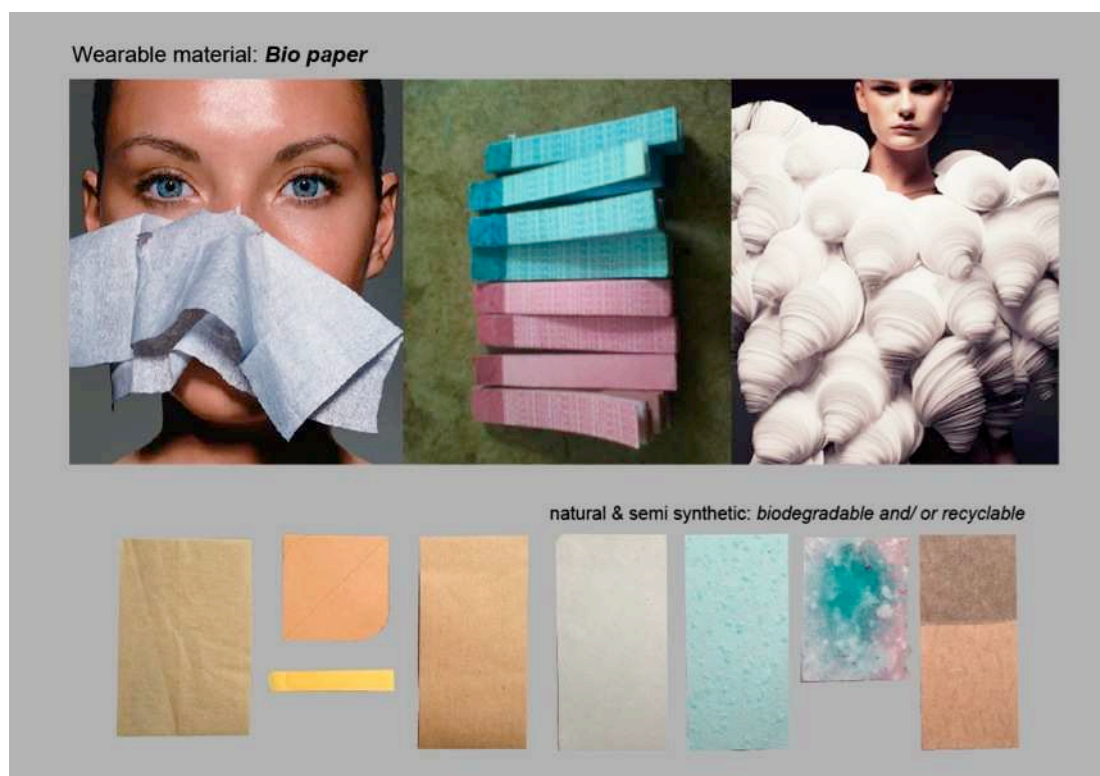


Fig. 10.35: *Bio Sense* material board 'Bio paper' (Prahl, 2014): (a) facial blotting paper image, (b) litmus paper image, (c) paper fashion (Bea Szenfeld), (d) various commercial samples: facial blotting paper, Frownies facial paper, litmus paper strip, Kraft paper and adhesive tattoo cover, (e) hand-made samples: cotton rag paper, thermochromic pigment dyed paper, thermochromic pigment dyed and painted paper (Prahl, 2014)

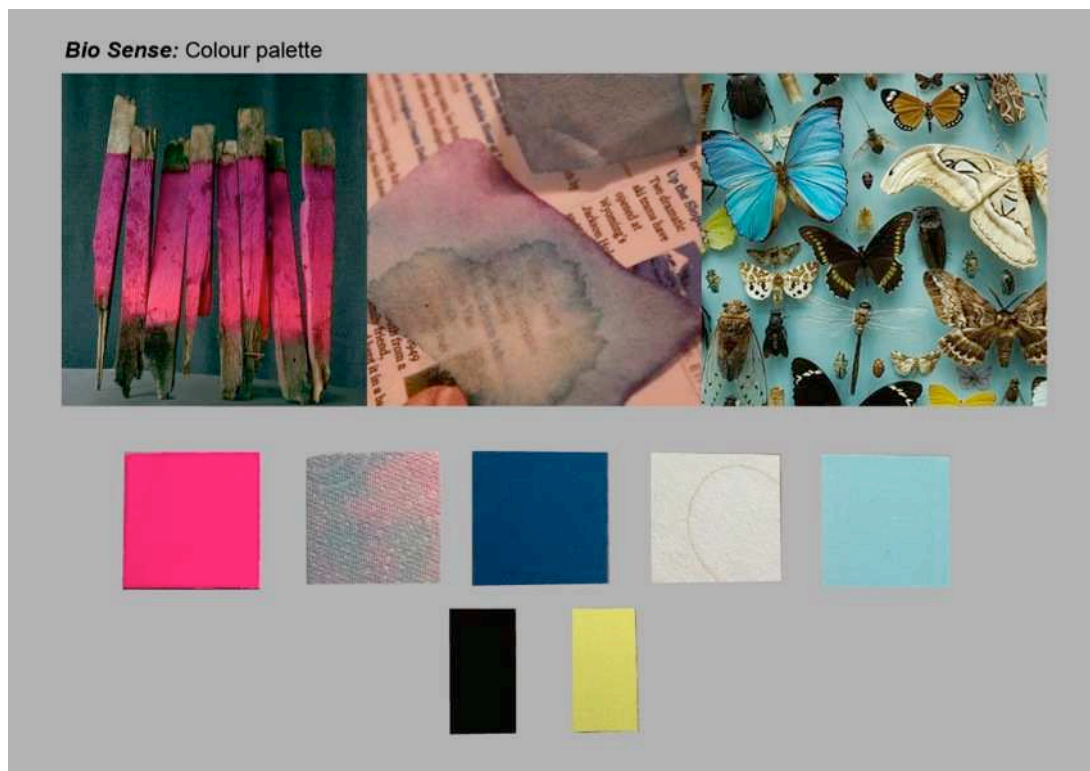


Fig. 10.36: *Bio Sense* colour palette board (Prahl, 2014): (a) magenta stained wood (Thomas Albdorf), (b) red cabbage dyed paper image, (c) butterfly and insect colour image, (d) various colour swatches

The colour palette consists of bright fuchsia, faded cabbage purple, deep blue, dipped off-white and light blue, with dark brown contrasts and lemon sorbet highlights (fig. 10.36).

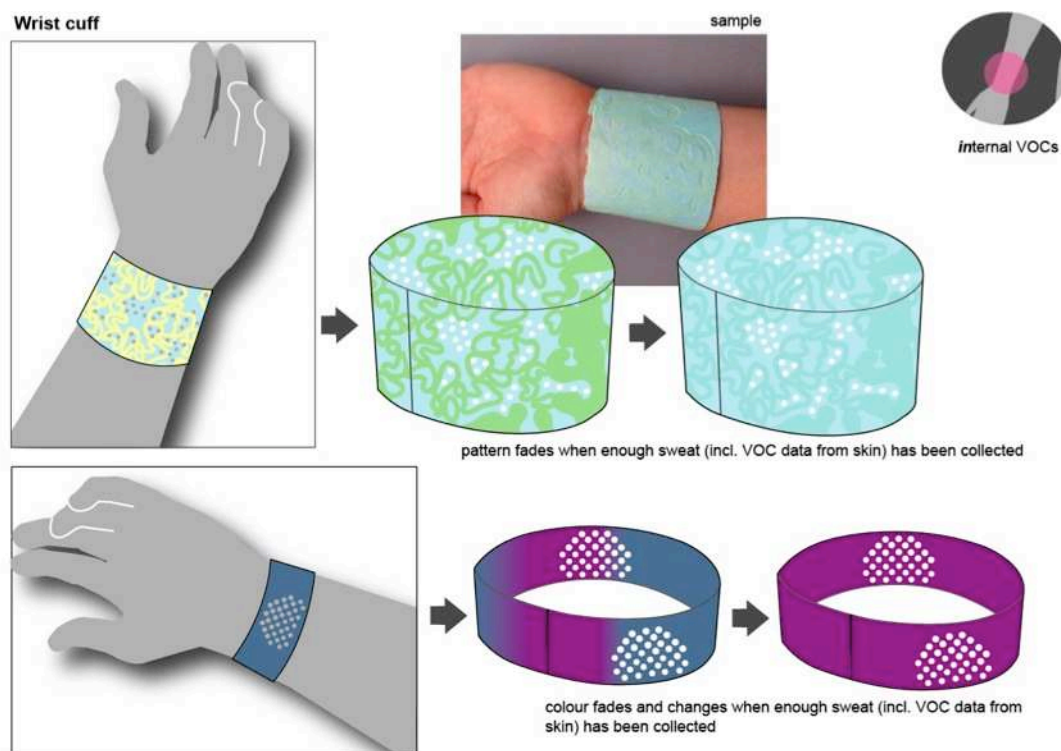


Fig. 10.37: *Bio Sense* designs and hand-made samples (Prahl, 2014)

Designs and samples included adhesive paper patches (fig. 10.37), paper-like tape (fig. 10.38) and wristbands (fig. 10.39).

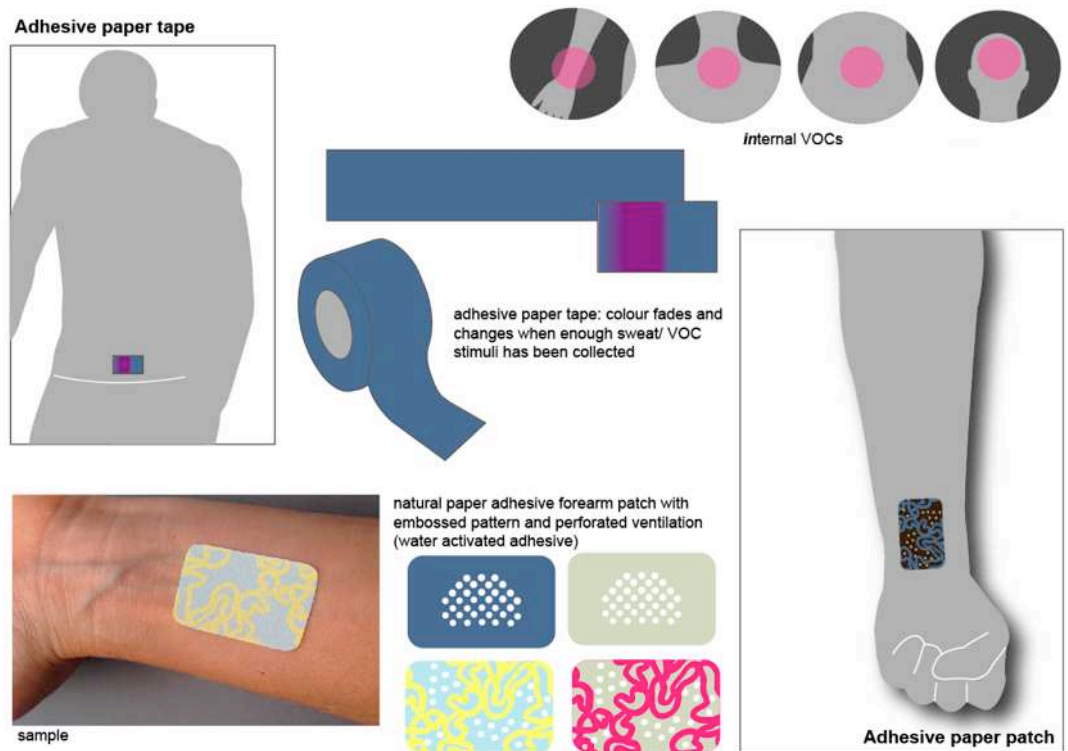


Fig. 10.38: *Bio Sense* designs and hand-made samples (Prahl, 2014)



Fig. 10.39: *Bio Sense* hand-made samples and commercial sample mock-ups (Prahl, 2014)

SENSOR ECOSYSTEM:

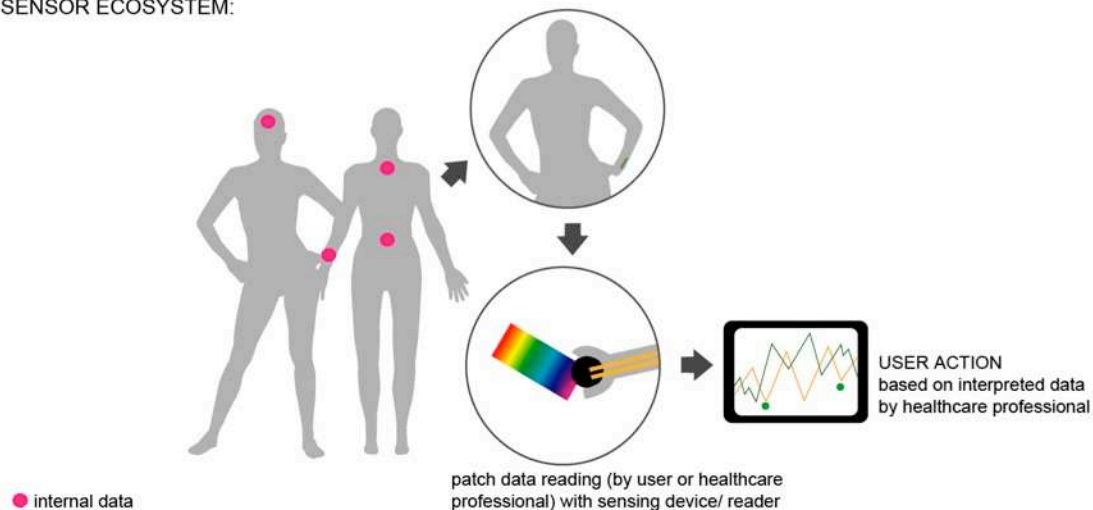


Fig. 10.40: *Bio Sense* sensor ecosystem diagram (Prahl, 2014)

This collection focused on the sensing of internal VOC data and relies on simple and low-tech colour feedback, simply to indicate that the paper-based substrate has been ‘saturated’ with enough sweat or skin-based stimuli to produce the required data. Once the paper has soaked up these stimuli, either the user or a healthcare professional can utilise a simple handheld sensing device/ transmitter to read and transfer the data for interpretation by a healthcare professional, so that the user can take appropriate action (fig. 10.40).

10.2 Artefact collections in context

Following the conclusion of the research project, the design outcomes, specifically the collection of the conceptual industry-facing artefacts presented in this chapter, will be considered for dissemination through appropriate methods such as publishing the thesis, writing and presenting papers at conferences, editorial writing and collaboration with stakeholders from industry and academia, in order to develop some of these conceptual ideas further in the future. At this stage however, it is necessary to reflect on the artefacts created, so that the design outcomes and methods utilised can be communicated as part of the thesis.

10.2.1 Artefact reflection: *Material, form and function.*

The design and development of textile-based Wearable Technology is a complex endeavour and would normally require multi-disciplinary teams consisting of various experts, such as product and textile designers, electronics engineers, scientists and user experience designers. However, I drew upon my professional background as a textile, clothing and accessory designer and chose to explore the perspective I could bring to the design of wearable sensors. As a result, these collections display distinctive concepts for the design and use of materials and form factors, as well as particular functional aspects, such as user feedback and interaction, as they have an impact on the design of material and form. Moreover, the artefacts demonstrate aesthetic diversity, which was achieved through the application of speculative user preferences, such as colour palettes, textile design and graphic elements and customisation opportunities.

MATERIAL: Wearable, end-of-life considered nonwoven sensor substrates

With regard to the development of new types of wearable end-of-life considered materials, the collections integrated the design of biodegradable or recyclable nonwoven rubber-like, felt-like and paper-like substrate samples, in order to provide potential end-of-life options. The collections included five material concepts; 'Tech skin' (synthetic: reusable & recyclable), 'Tech paper' (synthetic: reusable & recyclable), 'Bio film' (natural: biodegradable and/ or recyclable), 'Bio-tech felt' (natural or synthetic: biodegradable and/ or recyclable) and 'Bio paper' (natural or semisynthetic), all of which inspired a selection of designs and samples that expressed exciting prospects to re-think conventional textiles and explore what a *wearable material* could constitute. This approach could provide more cost-effective and diverse options for developing new types of environmentally considered materials to utilise in textile-based Wearable Technology such as clothing and accessories. Furthermore, the consideration of wearable materials such as natural and synthetic rubber, thermoplastic and silicone from other fields, which can utilise alternative types of manufacturing, could provide other benefits, such as the formation of substrates around the contours of the body, in order to provide better comfort and fit.

The collections also highlighted that if wearable sensors are to become ubiquitous and affordable devices utilised as part of a regular preventative lifestyle routine, they could be designed to provide more varied options on sensor use and lifespan,

subject to required wear times and wear frequencies in line with the stimuli to be sensed and printed enabling technologies utilised. Whether these wearable sensors are designed to be disposable or reusable, they should be biodegradable or recyclable at end-of-life, although certain considerations will affect these end-of-life solutions. Many types of medical devices are considered biohazards and must therefore be destroyed, and this will need to be considered in the design of wearable sensing devices, subject to their classification as a medical or general device. In the US, body fluids such as sweat, urine and tears are not considered hazardous, unless they contain blood, although this may change in the future or vary in different regions or countries. Furthermore, subject to where the stimuli occur on the body or in the environment and what type of stimuli they detect and monitor, these wearable sensors might need to be designed as single or short-term use devices, due to contact with sweat or other substances that may contaminate future data, unless they can be wiped clean.

In regard to disposability and recyclability, this research project was limited to the investigation of sensor substrates and further collaborative investigation will be necessary to address solutions for end-of-life options for any of the wearable sensors' printed, electronic and conductive elements, should these concepts be developed in the future for further academic or commercial use. However, these speculative concepts are built on the knowledge that promising research into transient electronics, triggered degradation and design for disassembly (chapter 6) could inspire future solutions for wearable sensors designed as part of a closed-loop strategy.

FORM: Non-integrated form factors for in-situ wearable sensors

Concerning the investigation of opportunities for non-integrated form factors, the collections build on the knowledge generated during the examination of non-integrated form factors (chapter 7) and propose a range of on-body locations for in-situ sensing, while presenting skin-worn, body-worn or clothing-attached wearable sensors, which could enable easy integration into the user's existing routines and outfits. Informed by research into ideal sensing locations and user feedback, on-body locations explored in the collections include the forehead, forearms, back, neck and feet (internal VOCs) and chest, head, forearms and legs (external VOCs and EMR). User research (chapter 7) showed that there are definite preferences for where on the body sensors are worn and these were reflected in the creation of the artefacts. However, options for whether a sensor is used as a visible accessory or

concealed within clothing depends both on individual user preferences and requirements in line with stimuli locations and these factors will need to be reflected in any further developments.

Most of these non-integrated wearable sensor concepts were designed to be applied directly to the skin or attached to or inserted into clothing, accessories or footwear and would therefore require some form of adhesive. A diverse range of commercially available samples utilising skin and clothing-compatible adhesives were presented in chapters 6 and 7. Adhesive manufacturers like Adhesives Research ^{10A}, based in the US and Ireland, specialise in developing application-specific adhesives, subject to end-use, material substrate, wear times and frequency and required properties (i.e. breathability, strength, minimum skin trauma, repositionability) and already manufacture electronically conductive, skin-friendly, medical and transdermal adhesives for an extensive range of applications across healthcare and electronics. Although wear times and frequency will depend on the stimuli to be detected and monitored (i.e. biochemical and environmental sensing), these conceptual collections are designed to consider various generic scenarios, such as daily, weekly or monthly wear, with wear times between an hour and several hours per wear. Should these concepts be developed further in the future, it will be essential to select and develop both suitable material substrates and adhesives for the specific wear time and frequency required, in line with the particular stimuli to be detected monitored.

The concepts presented in this chapter transferred emerging types of non-integrated wearable sensors from the specialist and medical realm into general lifestyle use. Furthermore, they demonstrate opportunities for the design of versatile and potentially cost-effective types of wearable sensors, which could be considered viable alternatives to garment-embedded products. In particular, these collections highlighted the scope for exploring stimuli-location inspired on-body positioning, which provides both concealed and visible wearable sensor options in line with user preferences or situations, while demonstrating that these non-integrated skin-worn, body-worn, and clothing-attached wearable sensors, could offer possibilities for the design of easy-to-wear devices, which could enable the wearer to actively engage in a regular sensing routine.

Moreover, the 'Wearable Skin' collection in particular illustrated that these types of sensors would allow the user to combine different types of on-body sensors to

monitor a combination of biochemical, physiological and environmental stimuli, in order to gain a more personal and complete overview of their health and wellbeing. However, despite the obvious opportunities, in particular view to environmental sensing, it is questionable whether sensors would need to be wearable at all, as mobile, portable or hand-held devices could do a similar, or better job. Any additional future developments would need to investigate the benefits of wearability over mobile, portable or hand-held devices, in line with the actual stimuli to be detected and sensing technologies utilised in the context of particular user scenarios and circumstances.

FUNCTION: Early warning, detection & monitoring system

The collections explored the design of wearable sensing devices, which are capable of detecting and monitoring biochemical and environmental stimuli and each individual collection considered which types of stimuli might be relevant for each of the five user types. The user research indicated that there are varying levels of acceptance of the potential harm that can be caused by external stimuli, such as the effects of exposure to EMR (chapters 8). Furthermore users expressed concerns about the use of Wearable Technology, in particular if items are connected to smartphones and other electronic devices, as this could exacerbate exposure to EMR from the very devices that are used to enable the wearable sensors.

Indeed, these considerations are surfacing on a wider level as various healthcare professionals, medical experts and scientists have recently been expressing their concerns in regard to the potential health risks associated with the use of Wearable Technology (Crothers, 2014). Although most Wearable Technologies utilise Bluetooth technology, which emits much lower levels of radiofrequency, cellular-based smartphones and other devices that use Wi-Fi are increasingly seen as a potential threat to human health (*ibid.*). The concepts integrated these concerns, as the 'Bio Sense' collection proposes non-electronic, low-tech wearable sensors, which simply soak up and collect sweat-based data that can be read and analysed away from the body. Furthermore, the 'Mindful Measure' collection explores the idea that while information on the potential dangers of exposure to EMR is still inconclusive, users may want to contribute to research in this field by pioneering the use of EMR responsive sensors themselves.

Wearable sensors and systems can provide diverse options for user feedback and interaction and the collections demonstrate these choices in line with potential user

preferences by proposing user feedback through: a) the wearable sensor itself, b) a connected mobile device such as a smartphone or c) through a central data collection unit, which could be managed by nominated healthcare professionals. The type of feedback relates to the stimuli sensed (i.e. biochemical or environmental) and whether the user needs to know (and potentially be alerted to take action) immediately, or whether they are collecting data to be interpreted by a healthcare professional, before appropriate action is taken. In order for this to work, the wearable sensing device needs to be part of a wider ecosystem, which can include other sensors, devices, apps and services, and often involves a central data unit managed by professional advisors and decision makers, depending on the user's health situation and requirements.

The collections emphasise opportunities for designing early warning, detection and monitoring devices, however, while these can benefit from being connected to a wider ecosystem, there are a range of issues which need to be investigated when designing such devices and systems. In addition to the potential health impacts of utilising cellular-based and Wi-Fi enabled devices to connect wearable sensors, there are concerns about data security and misuse (i.e. data accuracy, security and misuse by others), as well as impacts on user behaviour. This could include distraction and dependency on data, which could lead to the user developing hypochondriac tendencies and becoming dependant on constantly needing to check their health data and worrying about the outcomes. The collections therefore suggest different options for data feedback and user interaction, which involve less or more active involvement by the user. Moreover, two of the collections consider opportunities for crowd-sourcing, which allows the wearer to gather and combine external VOC data from other users with their own, in order to get a more accurate understanding of the potential health threats from ambient pollution.

10.2.2 Additional considerations for future development

In addition to the considerations outlined above, there are further issues to acknowledge. Although none of the topics listed in this section (enabling technologies & ecosystems, power generation and management, data contamination, the need for medical certification and user adoption rates) were considered to be within this project's scope and have not been explicitly explored as

part of this research, they constitute relevant factors for any future development of the ideas and concepts presented.

Enabling technologies & supporting ecosystems

It is essential to put the artefact collections in the context of key existing and emerging technologies, in order to gauge how they could be developed into working prototypes or proof-of-concept samples in the future. Chapter 2 presented various examples of printed sensing technologies, circuits and interconnections. These range from a) biochemical sensors and electrodes printed onto textiles, b) paper-like, tattoo-like and plaster-like substrates, to c) electronic elements and circuits printed onto flexible and plastic materials, and highlighted the promising opportunities for the commercial development of printed enabling technologies for wearable sensors.

The artefact collections therefore focused on exploring printed enabling technologies by conceptually integrating a range of technologies, such as painting or printing electronic circuits and sensors directly on the skin, ink-jet printing circuits and switches onto paper, paper-like and film substrates and transfer printing sensing and electronic elements onto latex rubber substrates and films. All of these approaches have validity in the context of existing and emerging technologies and although some of these innovations are still limited to academic research and prototypes, others, like printed electronics on paper, are already successfully used in the commercial realm, albeit for different products such as packaging, while some of the transfer printed plaster-like and tattoo-like sensors are considered close to commercialisation ^{10B}.

In order to provide feedback to the user or their nominated healthcare professional as part of a wider ecosystem, the wearable sensor needs to be able to communicate with, or be read and interpreted by another device. Yilmaz, Foster and Hao (2010) identified the three main types of wireless communication technologies between on-body sensors and any data capture unit as: a) off-body, b) on-body and c) in-body wireless body-centric communication. 'Off-body' describes data transfer between a device that is located on the body with one or several devices that are located off the body, while 'on-body' describes communication between several devices that are all located on the body and in-body refers to communication between devices that are implanted inside the body (*ibid.*). Examples of off-body wireless communication include Under Armour's E39 compression shirt (chapter 3), which can transfer data sensed and measured from the athletes to their coaches'

smartphones, tablets and PCs via Bluetooth and the sweat sensing patch developed at the University of Cincinnati^{10C} in 2014, which can communicate wirelessly via a smartphone app to inform the user about biomarkers, such as lactate levels, detected in their sweat during exercise. Another approach is to utilise smartwatches or other additional devices to read the skin or body worn sensor and this is illustrated by Electrozyme's armband, also developed in 2014, which is worn over their tattoo-like sweat sensor to transmit the sensed information to a mobile device, such as a smartphone, in real time^{10D}.

Power generation and management

One of the key barriers to the success of Wearable Technology is the generation, storage and management of energy to power the devices (Hurford, 2009). However, most wearable sensors only require small amounts of power, which could be supplied via connected electronic devices, printed or other types of miniaturised batteries or Bluetooth low energy systems. Furthermore, this project was carried out in the knowledge that there are many ongoing research projects into alternative power sources, both in the academic and industrial realm, and these investigate the generation of solar^{10E}, kinetic^{10F} and thermal^{10G} energy in order to produce self-sufficient wearable devices. The latest and most relevant example for this project is based on epidermal power generation, and this technology has been investigated by Joshua Windmiller at the University of California, San Diego, who investigated power generation from perspiration as part of his PhD research into printed bioelectronics^{10H}. Windmiller's tattoo-inspired biofuel cells can process a wide range of 'biofuels' such as glucose, alcohol, lactate (in perspiration) and uric acid (in urine) and his ultimate goal is to pair the cells with smart sensors for which they provide power (Windmiller, 2013).

Data contamination

With a particular view to designing devices for biochemical sensing, it is also important to consider that surrounding chemicals or other substances, such as deodorants, soaps, moisturisers or dyes from clothing, could potentially contaminate the particular stimuli (i.e. VOCs) to be sensed from the wearer's skin and body. In a laboratory setting, these interfering factors can be eliminated. However, this would be difficult when biochemical sensing takes place as part of a general routine, as users are unlikely to want to make changes to their habits and types of products they are using. If a wearable sensor is designed to be reusable, it must therefore also be washable or wipeable, so that any remnants of previously collected samples

can be eliminated. Further research into how to design the sensors to avoid data contamination or whether single-use sensors would be more appropriate, should be carried out to make sure that readings will be accurate and reliable.

Medical certification

Although the FDA has defined some basic regulatory information (FDA, 2012) on what constitutes a medical device, designers need to be aware of the current grey zone around the classification of medical and general lifestyle devices (chapter 2) in their specific field and global location. As this research applies knowledge from the specialist and medical realm to investigate the design of lifestyle integrated wearable sensors, these concepts blur the lines between medical and lifestyle products in order to encourage users to wear these devices as part of existing routines. Therefore it will be critical to establish whether any academic developments or commercial products inspired by these collections would need to gain certification, or whether there are ways to design these sensors that could avoid the need for certification, while making sure that accurate data can be provided safely and appropriately.

User adoption

The success of wearable sensing systems depends significantly on high rates of user adoption, and this includes both adoption by the wearer (potential patient) and the healthcare professional. While this research has already addressed how to design sensors that could contribute to wearer adoption by integrating diverse user needs and preferences, it is also important to consider the involvement of relevant healthcare professionals in managing such wearable sensing systems, as the user needs to be supported in utilising devices and interpreting and acting upon the gathered data. Coyle and Diamond (2013) stated that one of the key challenges to overcome is the acceptance of Wearable Technologies by the medical profession and believe that studies on impact of quality of life, care and benefits are urgently required to convince the medical community of the adequate use of such wearable health systems in order to reduce the growing healthcare burden and provide preventative healthcare more efficiently. However, looking at the use of digital technology in healthcare in general, the report 'Healthcare delivery of the future: How digital technology can bridge the gap of time and distance between clinicians and consumers' (Health Research Institute, 2014), which was based on a survey of 1000 healthcare professionals, exposed that there is a noticeable shift in attitudes towards the use of digital technology, as there are clear indications of the growing

acceptance of the adoption of digital tools amongst physicians and clinicians. The report also highlighted that the next five years will be critical for the innovation and adoption of new technologies, in order to change the ways in which patients suffering from chronic illnesses are currently monitored (*ibid.*).

10.3 Conclusion

Stimulated by the five-part design brief (chapter 9), which embedded the potential attitudes, needs and preferences of five speculative user types, these five collections showcase how wearable sensing devices could be designed to integrate more easily into user's existing lifestyles, routines and outfits, so they can appeal to a diverse range of users. In particular they: a) convey the promising potential for the creation of new types of wearable material substrates designed with various end-of-life solutions in mind, b) highlight the scope for non-integrated skin-worn, body-worn, and clothing-attached wearable sensors in a lifestyle context and c) provide ideas for early warning, detection and monitoring devices, which, as part of a wider ecosystem, can offer appropriate and diverse feedback and interaction. Thus the thesis proposes that these artefacts display convincing opportunities for the design of new types of wearable, textile-based biochemical and environmental sensors as part of a preventative healthcare approach and could therefore form the basis for additional and more specific academic or commercial research, design and development in the future. However, several aspects need to be considered, should these collections be utilised by other design researchers or practitioners to inform and inspire future work.

Firstly, beyond the limited feedback on selected elements of the design practice through dissemination of several papers (Prahl, 2013, Prahl 2013a, Prahl 2013b, Prahl, 2014a), there has been no significant opportunity to test and evaluate the final artefact collections with the intended target audience (i.e. key stakeholders in the Wearable Technology community such as researchers, designers, developers, engineers or scientists). Therefore these concepts remain a proposition to be examined and it will be essential to present and disseminate these collections within the Wearable Technology community in the future to receive valid feedback on their intended purpose. Although this lack of external evaluation may be considered a drawback in terms of the validity and reliability of the research outcomes, the focus on the research and design of the design brief and final artefacts provided the

opportunity to go into great depth in order to present more refined collections, which I am keen to test and evaluate as part of proposed future work (chapter 11).

Secondly, I consciously chose not to involve the user in the evaluation of these collections, as the artefacts were intended to be industry-facing and are not designed as proposals for commercial products. The user played a significant role in stimulating various elements of the design practice (chapters 6, 7 and 8), the subsequent creation of the design brief (chapter 9) and in providing inspiration for the design of the collections (chapter 10). However, in the context of how the artefacts are intended, my focus remains on how the Wearable Technology community could work with these concepts in the future to develop more refined and potentially commercial applications. Should other researchers and designers wish to build on these concepts, they may want to engage in additional research to evaluate some of the proposals from a user perspective (chapter 11).

Thirdly, I am acutely aware that in this fast-moving field of Wearable Technology, these wearable sensor collections could date relatively quickly. However, I believe they could further act as a valuable record of the evolution of textile-based Wearable Technology and wearable sensors in the future, while summarising relevant trends, consumer preferences, material choices and technologies, so particular aspects of these collections could be employed to inform and inspire additional future design work (chapter 11).

Chapter 11: Conclusion

This research explored the design of wearable sensors in the context of Preventative Health and was motivated by the identification, exploration and evaluation of particular gaps in knowledge. These gaps constitute compelling design opportunities (chapter 3) and provided the framework for the design research. The experimental, practice-driven research methodology enabled the development of a three-stranded, interdependent investigation into material, form and function and addressed a variety of exploratory research questions (chapters 6, 7 and 8), which generated a diverse range of data and artefacts, confirming that these opportunities would indeed benefit from further study and exploration:

- Wearable biochemical and environmental sensing is still under-researched and could be particularly efficient in a lifestyle context, where early warning, detection and monitoring systems integrated into the users' existing routines can engage the user in a preventative lifestyle in order to improve their long-term health;
- New types of non-integrated, skin-worn, body-worn or clothing-attached sensing devices could bring opportunities to incorporate wearable sensors into the users' existing outfits and activities more easily, while providing the tools to detect and monitor a range of personalised parameters, thus allowing for a more holistic and personalised overview of the user's health;
- Closed-loop material substrates, with a particular focus on nonwoven rubber-like, felt-like and paper-like synthetic and natural materials, could make significant contributions to the design and development of end-of-life considered wearable sensor concepts for regular use;
- Building on existing user-centred design approaches and methodologies from the broader context of design, the exploration of creative approaches for the integration of a thorough user-needs investigation into the early stages of the design process could be particularly relevant in the realm of Wearable Technology, where stakeholders are often criticised for cashing in on fleeting trends, as consumer's needs are overlooked in favour of pushing new technologies onto the research agenda and market place.

Subsequently, the diverse findings and conceptual conclusions generated during these interdependent creative investigations were synthesised to inform and formulate the design brief (chapter 9), which addressed the potential needs of five speculative user types for wearable sensors, with a particular focus on material, form and functional aspects. The design brief facilitated and stimulated the design and development of the conceptual wearable sensor collections, which explore and demonstrate how wearable sensors can be designed to integrate more easily into the user's existing lifestyle, routines and outfits, as part of a preventative healthcare approach (chapter 10). Furthermore these artefact collections embed specific proposals for biodegradable or recyclable, natural or synthetic nonwoven material substrates and non-integrated form factors, including skin-worn, body-worn or clothing-attached wearable sensors, so that the artefacts could be utilised to stimulate debate and further collaborative research, design and development of wearable sensors in the future.

This chapter presents the outcomes relating to *context*, *practice* and *practice methodology* and these are evaluated in order to communicate how they can contribute to knowledge in the field of wearable sensor design and beyond and propose how they could be used to build upon by other researchers and designers, while this chapter also suggests opportunities for further work, considering both the findings and limitations of the research. Findings and outcomes are documented throughout the thesis in the form of text, diagrams, photographs and other images, while the supporting digital storage device contains additional documentation of the user type concepts (design brief) and complete wearable sensor collections, in order to share them appropriately with other design researchers and practitioners.

11.1 Designing wearable sensors for Preventative Health: Contributions to knowledge

In order to achieve the overall aim of the research, which was to create an informative and stimulating, industry-facing collection of conceptual artefacts, I defined four key objectives (chapter 1), which were met through various research outputs:

1. The identification and documentation of key challenges, gaps in knowledge and design opportunities for textile-based wearable sensors

This objective was achieved through a general review of various issues and challenges for the design and development of textile-based Wearable Technology (Prahl, 2012, appendix A), the findings of an extensive contextual and literature review of textile-based wearable sensors, including their construction, materials and applications (chapter 2), and the documentation and evaluation of key challenges, gaps in knowledge and consequent design opportunities for the design of wearable sensors in the future (chapter 3).

2. The development and application of an experimental, practice-driven research methodology

In response to the identified design opportunities for wearable sensors and an initial phase of exploratory sampling (chapter 5), this objective was explored through the creation of a three-stranded research model focusing on material, form and function, which enabled the creation of research boundaries and formulation and exploration of particular research questions (chapters 6,7 and 8), while driving the selection and development of appropriate design research methods and tools (chapter 4).

3. The design and development of a collection of conceptual artefacts

The design and development of the conceptual artefact collections was facilitated through the application of the experimental research methodology, as the three-stranded investigation produced diverse data (chapters 6, 7 and 8), which was evaluated to formulate the design brief (chapter 9). The design brief subsequently informed and inspired the design and development of the final artefacts; the wearable sensor collections (chapter 10).

4. The evaluation of the final conceptual artefact collections and experimental research methodology

This objective was met through the documentation, contextualisation and evaluation of the wearable sensor collections (chapter 10) in regard to the research questions and their original intention. However, as there has been no significant opportunity to test and evaluate the final artefact collections with the intended target audience (i.e. appropriate stakeholders in the Wearable Technology community) they remain a proposition to be examined. The key elements of the research methodology are evaluated in chapter 4 and practice and practice methodology related contributions to knowledge, based on the use of the three-stranded research model and the creation of the artefacts, are presented in sections 11.1.2 and 11.1.3.

Contributions to knowledge: Context, practice and practice methodology

This research produced a range of interlinked findings and outcomes (fig. 11.1), which contribute to the overall understanding of the field of textile-based Wearable Technology and the research, design and development of wearable sensors in the context of Preventative Health in particular.

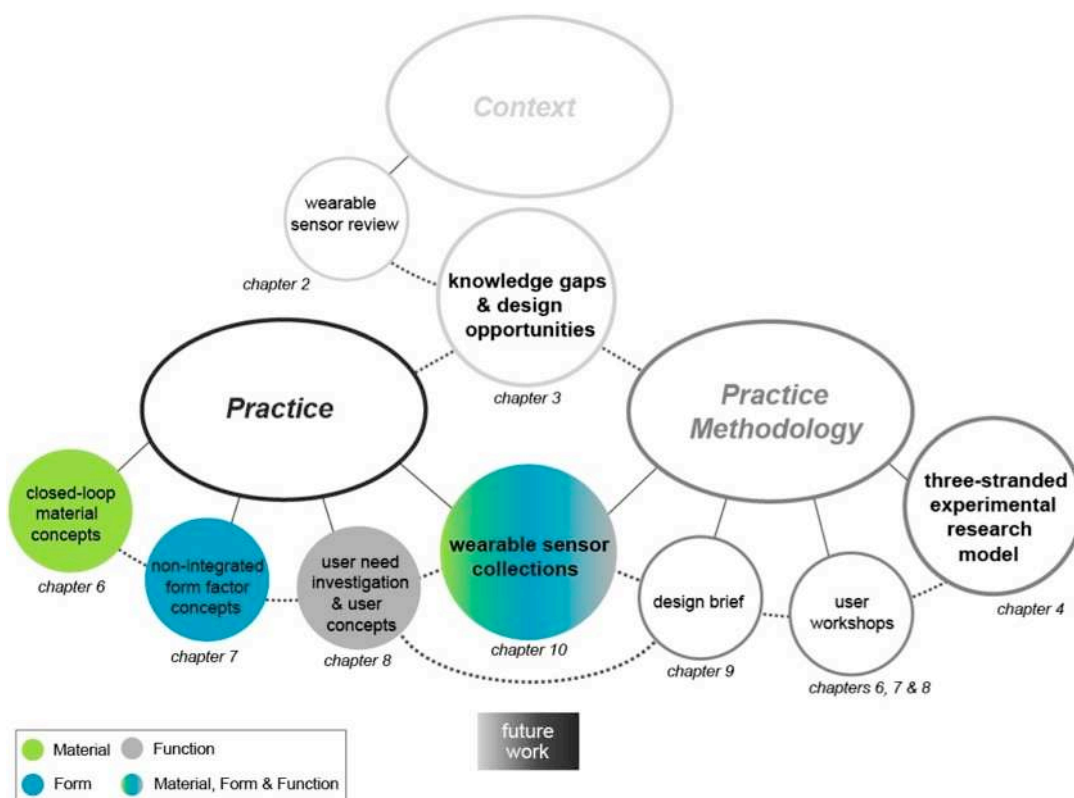


Fig. 11.1: Summary of research outcomes and contributions to knowledge, Prah (2015)

In line with the combination of practice-based and practice-led elements (chapter 4) and the importance of the rapidly evolving background of the research (chapter 2), the findings and outcomes of this research constitute contributions to knowledge on three levels; a) the *context* of wearable sensor design (i.e. providing contextual research foundations for myself and others), b) the *practice* of wearable sensor design (i.e. generating outcomes that can contribute to the innovation of new types of wearable sensors in an academic and commercial realm, by myself or others) and c) the *practice methodology* of wearable sensor design (i.e. offering insights into methods and tools utilised in order to inspire the adoption or adaption of such methods by others in the future) and these contributions are relevant both in an academic and industrial context.

11.1.1 Contributions to knowledge: Context

Wearable sensor review and knowledge gaps & design opportunities

Contextual contributions refer to outcomes that can be used as a general foundation by others in the future, i.e. researchers and designers could utilise the contextual and literature review and/ or the subsequently identified challenges and design opportunities as a starting point to their own research, or could investigate one or more of the particular aspects in more depth. The state of the art overview of textile-based wearable sensors focused on more recent and emerging research and developments (2005-2015) and the synthesis of these findings facilitated the identification of current key issues and challenges in the field of textile-based Wearable Technology and led to the proposal of a series of emerging design opportunities worthy of investigation (chapter 3), which acted as the foundation for the project. The research therefore contributes to the understanding of the complex and emerging field of textile-based Wearable Technology in general and the design of wearable sensors in particular and beyond the use of these findings within this research project, they can be utilised by other researchers and designers in the future as a foundation to their own research.

Specifically, the research offers insights into opportunities around designing biochemical and environmental wearable sensors within the context of Preventative Health and presents both high-tech and low-tech approaches, by including non-electronic sensors in the enquiry. This approach allowed for a wider scope to include conceptual proposals for users who may not be willing to engage with

complex technical or electronically enabled products generally associated with Wearable Technology.

11.1.2 Contributions to knowledge: Practice

Contributions concerning practice (practice-based) include outcomes that can be applied in their entirety or in part and constitute new material and form factor concepts for the design of wearable sensors and user type concepts, based on a thorough user need investigation for a lifestyle-integrated early warning, detection and monitoring system.

New material substrate concepts for wearable sensors

The research identifies, classifies and proposes new types of wearable materials that could be suitable as sensor carriers, and these include rubber-like, paper-like and felt-like synthetic and natural nonwoven substrates, designed based on closed-loop principles (illustrated through an overview of commercially available, non-technical material swatches in chapter 7 and concept boards, design sketches and hand-made material swatches and samples in chapter 10). End-of-life, as well as other environmental issues, are currently severely under-researched and are therefore worthy of investigation. The contribution to knowledge lies in discussing and documenting these issues, following on from Köhler (2008, 2013), as well as providing conceptual design inspiration for suitable end-of-life options including recyclability and biodegradability.

In general, these concepts aim to encourage stakeholders to begin to integrate end-of-life design thinking into the early stages of the design process, so that meaningful academic and commercial innovation can take place in the future. Specifically, other researchers and designers can utilise the identification and classification of new types of wearable materials (rubber-like, paper-like and felt-like) and/ or the presented concepts for closed-loop material substrates (chapters 6 and 10) to develop additional work in the future.

Non-integrated form factor concepts for wearable sensors

The research further identifies, classifies and proposes new types of non-integrated wearable sensors, suitable for in-situ biochemical or environmental sensing, which could be skin-worn, body-worn or clothing-attached (illustrated through an overview

of commercially available, non-technical reference samples, chapter 7). The initial contribution to knowledge lies in highlighting the potential advantages and opportunities of non-integrated wearable sensors over clothing-integrated sensing, which is still the focal point of most academic and commercial research and development in a fashion and lifestyle context, despite obvious drawbacks (chapter 3). Building on revolutionary innovation around sensing tattoos, plaster and patches from specialist and medical fields (chapter 2) and expanding on existing research by relocating skin-worn wearable sensors into a lifestyle context, the wearable sensor collections demonstrate new possibilities for future design concepts (illustrated through concept boards, design proposals/ sketches and hand-made samples in chapter 10), in order to make these types of sensors wearable beyond current applications and as part of the user's existing habits, routines and outfits.

The wearable sensor collections demonstrate viable alternatives to permanent clothing integration and contribute to knowledge on how to approach the design of versatile wearable sensors that can be worn as part of an existing lifestyle. Furthermore, these concepts indicate initial possibilities for the development and manufacture of potentially more affordable and cost-effective types of wearable sensors, however this aspects needs further research and development. These concepts aim to encourage other designers and researchers to consider non-integrated form factors for future design projects and they can do so by adopting the identification and classification of skin-worn, body-worn and clothing-attached form factors (chapter 7) to develop their own concepts, or utilise the concepts presented as part of the wearable sensor collections (chapter 10) to build on.

User needs investigation and user type concepts

Based on extensive user-centred design research, including an intense phase of active community immersion (chapter 8), which provided authentic insight into users' potential attitudes, preferences, needs and wants, the research established the user need for wearable biochemical and environmental sensors to easily integrate into the wearer's existing routines, habits and outfits as part of a preventative lifestyle. Furthermore, in combination with the outcomes of the material and form investigations (chapters 6 and 7), this user need investigation contributed significantly to the creation of the speculative user types and subsequent user type concepts (design brief), which informed and inspired the design of the wearable sensor collections (chapter 10).

The contribution to knowledge is demonstrated through the gathering, synthesis and presentation of this diverse qualitative data into the design brief (chapters 9), and other researchers and designers could utilise the findings in the following ways; a) to design concepts and products for the five identified speculative user types, b) to inform their own identification and development of speculative user types of textile-based Wearable Technology, or c) to test and develop the proposition that wearable sensors capable to function as an early warning, detection and monitoring system, should be designed to integrate easily into the user's existing lifestyles, routines and outfits.

11.1.3 Contributions to knowledge: Practice methodology

Practice methodology (practice-led) outcomes concern findings that provide insights about design practice and include the three-stranded research model, the user workshops, the design brief and the conceptual artefact collections. In line with a deductive research approach, where a theory is tested, confirmed, denied, modified or expanded upon, researchers and designers could therefore adapt the structure and format of the three-stranded investigation, the user workshops, the design brief and/ or the collection of conceptual artefacts, in order to test or replicate the design research in their own manner, thus recreating or constructing new design artefacts in the future, subject to their specific design inquiries and research contexts.

Three-stranded research model

The research presents the selection and development of suitable practice-based research methods and tools and introduces an experimental three-stranded approach, which merges material, form and function into one original investigation. The contribution to knowledge comprises the combination of these three key areas and their related research questions and the development (chapter 4), application and evaluation (chapters 6-10) of this creative approach, which could be utilised or modified by other design researchers and commercial designers in the field of textile-based Wearable Technology, or transferred to or tested in other design contexts.

User workshops

Two different user workshops were developed and utilised as part of this research and these focused on the investigation of material and form (workshop 2, chapters 6 and 7) and function (workshop 1, chapter 8). Utilising user workshops within design research is not an original choice of method, as they are established tools both in academia and professional practice. However, these workshops constitute an integral and significant part of the user-centred enquiry, which aimed to explore creative approaches for the integration of a thorough user needs investigation into the *early stages* of the design process and were preceded by user research, community immersion and an intense phase of active participation. Furthermore, these workshops were developed and employed specifically to elicit responses around design concepts and scenario building for my own design work and led to the development of the user type concepts (design brief) and subsequent design of the wearable sensor collections.

Thus the contribution to knowledge is demonstrated by the pivotal role these user workshops played as part of the design practice and can encourage other researchers and designers to consider how this method could be adopted or adapted for their own research, in order to generate inspiring and relevant data.

Design brief (user type concepts)

Merging key findings from the material, form and function investigations (chapter 6-8), the creation and application of the experimental design brief (chapter 9) provided a stimulating creative space to explore the potentially very different user attitudes, needs and preferences and therefore had a significant impact on the diversity of the final collections of artefacts and overall design outcomes of this research. The initial contribution to knowledge lies in the gathering, synthesis and presentation of this diverse qualitative data, which has several future applications in the academic and industrial realms. Professional practitioners could utilise the design brief (user type concepts) as an inspiration for the design and development of new Wearable Technology devices, or could utilise and build on the identified user types or data presented in the artefact chart (fig. 9.3) to inform their own design brief for future research and products. Moreover, academic design researchers could test and evaluate the identified user types concepts as part of their own research, or, based on the findings presented in chapters 6-8, recreate their own user profiles and user concepts to suit their particular research.

Although, both in academic and commercial contexts, the use and development of user profiles and design briefs are established tools for the creation of new concepts and products already, the contribution to knowledge further encompasses the combination of both elements into one imaginative format (section 9.2), as well as the documented collation of research data into the artefact criteria diagram (section 9.1.2, fig. 9.3), which further guided the design brief and the demonstration of the application of the design brief, resulting in the wearable sensor collections (chapter 10).

Conceptual artefact collections

In addition to the practice-based contributions around material, form factor and user type concepts, the conceptual wearable sensor collections can contribute to understanding *about* practice, as they demonstrate how gathered data and research findings can be embedded, presented and communicated through artefacts, in order to provide stimulating formats for design inspiration, both for the design researcher/practitioner or their target audience. The format of these collections (i.e. concept boards, swatches, design sketches and samples) is an established and essential qualitative research and visualisation tool in many specialist fields of design, and therefore does not in itself constitute new knowledge. However, the application of these well-known tools, in this, for me, previously unexplored research context, provided a structured method to rise to the challenge of working in an unfamiliar territory and this could suggest that other design researchers and practitioners might also benefit from the use and development of familiar tools and methods, in new design contexts. Furthermore the advantages of utilising exploratory artefacts as drivers of design practice during the definition stages of the project, as well as a collection of final artefacts to express the overall findings of the research, has been clearly demonstrated.

Beyond their role as part of the research project and thesis, these collections of final artefacts are further intended to stimulate discussion and new possibilities for cross-disciplinary research, design and development for the design of textile-based Wearable Technology in the future. However, as I have not been able to test the collections with their intended audience, there can be no claims on contributions to knowledge in regard to their intended impact, therefore the testing and evaluation of these five collections constitutes an essential element of any future research emerging from this research (section 11.2).

11.1.4 Reflection & evaluation

Inspired by my critical stance on the domain of Wearable Technology, the research originally set out with the general intention to produce a collection of artefacts that could address specific issues, challenges and resultant design opportunities, in order to present outcomes that could stimulate and inspire collaborative additional work in the future. Some of these opportunities have previously been explored independently; a) Köhler's work (chapter 3) on identifying and communicating the potential end-of-life issues around textile-based Wearable Technology and developing experimental tools to address these (Köhler, 2008, 2011, 2013; Köhler, Hilty and Bakker, 2011); b) promising research and development on non-integrated wearable sensors in specialised and science-based fields such as health & medical and high performance sports (chapters 2 and 7); and c) user-centred design approaches utilised in the broader context of design research (chapter 8), have been highly inspirational to my own research. However, this research builds on previously generated knowledge, as my understanding of textile and clothing design has brought new perspectives to some of these emerging concepts and applications, by situating the research in an everyday lifestyle context. Furthermore, this research project synthesised these diverse design opportunities as interconnected concepts through a three-stranded, practice-based investigation into material, form and function and this approach has enabled a diverse range of contributions to knowledge, ranging from outcomes concerning *context* and *practice* to outcomes regarding *practice methodology*, all of which can be applicable both in academic and professional practice contexts.

Overall, and in line with my original intentions, this research project extends knowledge on some of the complex issues and challenges of designing textile-based Wearable Technology in general and wearable sensors specifically, while providing initial frameworks for the design of end-of-life considered and non-integrated wearable sensors, which can appeal to a broad section of users as part of a regular preventative lifestyle routine. In summary, these contributions provide a diverse knowledge base for additional work and suggest directions for other design researchers and practitioners, which will benefit from a collaborative and cross-disciplinary approach to develop these outcomes further.

11.2 Future research & work

Based on the evaluation of this project's findings, as well as the reflection on some of its limitations, I am able to identify and propose areas of future research that can further build on the diverse outcomes of this project. From the outset, this project aimed to contribute to the inspiration of stakeholders of the Wearable Technology community, with a view to encouraging additional, collaborative work around the key design opportunities addressed in this thesis. Therefore the research is defined by outcomes and contributions, which can be applied and further developed both by others and myself, in the broader field of textile-based Wearable Technology and, potentially also across a wider range of design-related fields, such as textile, clothing, accessory and product design, both in academic and industrial contexts. In line with my original intention to encourage and inspire debate and further research in this field, initial academic dissemination of particular elements of this research has already taken place by presenting several research papers (chapter 10), however, additional academic and industrial outputs, such as articles, academic papers and conference presentations, as well as opportunities for design collaborations, will be sought out in the future.

According to the research's overall proposition that wearable sensors should be designed to integrate easily into the user's existing lifestyle, routines and outfits, in order to engage a broad section of the population in a preventative lifestyle, the final collections of artefacts demonstrate how wearable sensors could be designed to fulfil this requirement (chapter 10). However, due to the inductive and exploratory nature and the particular scope of this research, this proposition was not tested as a hypothesis. Therefore one fundamental aspect of additional work should include the development and use of design-led methodologies to test this proposition, which could contribute both additional outcomes concerning *practice* and *practice methodology* in the future. In addition there are several key elements I would like to propose as a future research agenda and these include further work around the *context* of the domain of wearable sensors, the *practice* of designing wearable sensors and the *practice methodology* of designing wearable sensors or similar products.

11.2.1 Future work: Context

While this research has produced an extensive review of textile-based wearable sensors, their manufacture, materials and applications, focusing mainly on the period between 2005-2015, it will be essential to keep up-to-date with the latest emerging developments in this rapidly evolving field. Therefore, any researchers and designers wishing to utilise this review as a starting point to their own work, or build on the work presented in this thesis must engage in their own, additional contextual research to ensure the fast pace of innovation is recognised. This is particularly relevant in the context of designing for Preventative Health, where technology innovations, as well as emerging medical research and global socio-economic developments are critical factors.

11.2.2 Future work: Practice

These inevitable contextual changes will affect the practical work, as the wearable sensor collections and associated findings and outcomes could date relatively quickly. It is important that any designer or researcher utilising the practical outcomes to build upon, first considers their relevance in this constantly evolving sector, subject to new materials, technologies, applications and other contextual factors.

Material concepts

The concept of design for disassembly was originally addressed in the exploratory sampling stage (chapter 5), however, this avenue was not explored any further during the subsequent design practice. Therefore, future work should include a specific investigation of how these wearable sensors could be designed for disassembly and reuse, if they use recyclable substrate materials. Furthermore, this project was only able to consider the wearable sensor's main material substrate and excluded any printed, electronic and conductive components and in order to provide more refined concepts, it will be necessary to investigate biodegradability or recyclability for the entire wearable sensor, which would require collaboration with electronic engineers and scientists with expertise in printed and transient electronics, triggered degradation and design for disassembly (chapter 6). Another element is the exploration of what a 'wearable material' could constitute. This research has already contributed to knowledge in regard to the creation of new types of

substrates, however, these would further benefit from exploring formation of materials around the contours of the body, thus conceptually merging material and form, to provide ultimate comfort and fit. This research further indicated that there might be promising opportunities to produce cost-effective and affordable wearable sensing devices (chapter 10), utilising synthetic or natural nonwoven substrates. Building on these initial findings based on available commercially available materials samples (chapter 6) and hand-made swatches and samples (chapters 5, 6 and 10), this aspect still requires special attention and additional research and development.

Form factors

This project proposed non-integrated wearables as an effective alternative to clothing embedded biochemical and environmental sensing (chapters 3, 7 and 10), which can be worn in an everyday lifestyle context. However, more research, design, development and dissemination will be needed to explore potential types, shapes and silhouettes further and this is especially pertinent, as the Wearable Technology community (both academia and industry) is currently preoccupied with the development of seamless integration into clothing, which could cause the creation of a new electronic textile waste stream (Köhler, 2008). Therefore stakeholders need to acknowledge these challenges and must commit to developing and implementing solutions to this potential problem, before these types of products become ubiquitous commodities.

User needs investigation and user type concepts

This research validated the user need for wearable biochemical and environmental sensors, which can easily integrate into the wearer's existing lifestyle and the wearable sensor collections were designed with this aim in mind. However, the final artefacts have not been tested or evaluated with any users, or indeed the particular speculative user types they were designed for (chapter 9). Therefore, it could be beneficial to evaluate these initial concepts with relevant user groups and types, in order to develop the concepts further and produce more refined proposals.

Additional suggestions

As a result of the loss of the collaborative aspect of this research (chapter 1), the wearable sensor collections were designed without a specific printed enabling technology in mind and this further resulted in the absence of proof-of-concept prototypes to support the conceptual artefact collections. I therefore propose additional work to build on these artefacts by utilising and testing particular existing

or emerging printed enabling technologies to create working prototypes that could illustrate these concepts in a more substantiated manner.

As previously mentioned (appendix A and chapter 10), there are other challenges and opportunities, which could be explored in relation to the research and outcomes presented in this thesis. These include the following:

- Environmental impact during manufacture (i.e. resource consumption and depletion, hazardous waste creation and pollution)
- Human impact during manufacture and at end-of-life (i.e. health hazards to workers and people in touch with electronic waste)
- Potential health hazards and negative physical or emotional impacts for the wearer due to wearing or utilising the device
- The wearable sensor and its supporting ecosystem (other devices, data transmission, software, apps, interfaces/ data display and services)
- Data security, privacy and user dependency
- Power generation, storage and management
- The challenge of product certification
- User adoption of wearable sensors (with a particular focus on healthcare professionals)

11.2.3 Future work: Practice methodology

The three-stranded research model was highly specific to the research project and it would be beneficial to test, evaluate and develop, if and how this approach could work for others both in an academic and industry context, so that the methods and tools used can be utilised and applicable to a broad range of designers and researchers in a variety of design contexts. The user workshops developed as part of the experimental research methodology were utilised to produce qualitative data, in order to enable the identification and development of five speculative user types, which acted as the design brief and informed and inspired the design of the wearable sensor collections. However, as described in section 11.1.2, it would be advantageous to develop and hold particular user workshops that aim to elicit user response to the wearable sensor collections, as this could reveal further insights into

the collections' relevance to and acceptance by the user, thus contributing to insights about the designed artefacts, as well as the method itself.

The design brief was based on five speculative user types and within the scope of this research, it was decided that five different types would be sufficient and that a unisex approach and a relatively broad age range (26 to 45) would constitute suitable parameters. However, further work could investigate and test whether a broader range of user types, a more particular focus on gender, or a more defined age range, could result in more complex or advanced artefacts. While this research contributed to the understanding of the use of different types and formats of design artefacts in practice-based design research, these collections were originally intended and designed as industry-facing artefacts, which could encourage debate, new ideas and future collaborations. However, as it was not possible to test the wearable sensor collections with their intended audience during this project, further work is needed to test and evaluate how the format of these collections would be received and understood. I therefore propose that these artefacts are tested in their current format (i.e. as academic papers/ presentations, professional conference presentations and exhibitions, or meetings with potential academic or professional collaborators), or can be further developed into new types of formats for particular opportunities of presentation and discussion, subject to the audience.

11.3 Final comments

Compelling advances in sensor-enabled, textile-based Wearable Technology have been made over the last 10 years across academic, conceptual and commercial projects (chapter 2). Many of these developments can be attributed to the emergence of the Internet of Things (IoT), which, through associated devices, technologies and services, has allowed for the innovation and development of highly innovative concepts and products, specifically across specialist medical and sports applications. In line with the paradigm shift towards Preventative Health, wearable sensors could provide much-needed solutions for the growing burden on global healthcare systems. Thus, this research produced original findings and outcomes around the design of wearable sensors through the presentation and discussion of end-of-life considered, nonwoven (rubber-like, paper-like and felt-like) material substrates and non-integrated (skin-worn, body-worn and clothing-attached) form factors, while providing unique insight into users' potential needs and preferences

for wearable early warning, detection and monitoring devices, as part of a preventative lifestyle.

The research accomplished the overall aim to design and develop a collection of artefacts that demonstrate various issues, challenges and solutions in order to advance design innovation for textile-based wearable sensors and the contributions to knowledge presented as part of this thesis can therefore provide a foundation for a diverse range of additional future work. However, as many researchers and practitioners engaged in the domain of textile-based Wearable Technology have stated before me (Lee, 2005; Chang, 2005; Seymour, 2010; Dunne, 2010), and highlighted by some of the outcomes and limitations during this speculative project; unless we develop and support more appropriate methodologies for cross-disciplinary design research and development, any contributions to knowledge are likely to remain incremental, rather than producing revolutionary innovation.

Moreover, this need for collaboration does not only concern the cooperation of diverse disciplines including product, textile, user experience and service designers, product and material developers and scientists and engineers, but has to involve the advancement of appropriate methodologies and support networks for joint academic and industrial partnerships, in order to rise to the challenge of designing and developing effective wearable sensing devices and systems, which can contribute innovative, persuasive and cost-effective proposals for the future of preventative healthcare.

Bibliography

Publications: Books, journals, conference papers and theses

Archer, B., Badness, K. Langdon, R. and Roberts, P. (eds) (1979) *Design in general education*. London: Royal College of Art.

Ariyatun, B., Holland, R., Harrison, D. and Kazi, T. (2005) 'The future design direction of smart clothing development', *Journal of the Textile Institute*, 96 (4), pp. 199-210 [Online]. Available at: <http://www.tandfonline.com/doi/citedby/10.1533/joti.2004.0071#tabModule> (Accessed: 23/12/11)

Bergmann, J. H. M and McGregor, A. H. (2011) 'Body-worn sensor design: what do patients and clinicians want', *Annals of Biomedical Engineering*, 39 (9), pp. 2299-2312 [Online]. Available at: <http://www.ncbi.nlm.nih.gov/pubmed/21674260> (Accessed: 23/7/15)

Bergmann, J. H. M, Chandria, V. and McGregor, A. H. (2012) 'Wearable and Implantable Sensors: The Patient's Perspective', *Sensors*, 12, pp. 16695-16709 [Online]. Available at: <https://spiral.imperial.ac.uk/bitstream/10044/1/15350/2/Wearable%20and%20implantable%20sensors%3A%20the%20patient's%20perspective..pdf> (Accessed: 23/7/15)

Bhamra T. and Lofthouse, V. (2007) *Design for Sustainability*. Hampshire: Gower Publishing Limited.

Bidoki S. M., McGorman, D., Lewis D. M. and Miles, R. E (2004) 'Ink-jet Printing of Conductive Patterns on Textile Fabrics' [Online]. Available at: https://www.researchgate.net/publication/259439425_Ink-jet_Printing_of_Conductive_Patterns_on_Textile_Fabrics (Accessed: 20/1/15)

Biggs, M. (2004) 'Editorial: the role of the artefact in art and design research', *Working Papers in Art and Design* [Online]. Available at: <https://www.herts.ac.uk> (Accessed: 20/1/14)

Black, S. (2008) *Eco-Chic: the Fashion Paradox*. London: Blackdog Publishing.

Brosnan, M. J. (1998) *Technophobia-The psychological impact of information technology*. London and New York: Routledge.

Brown, T. (2009). *Change by design* [Online]. Available at: <http://www.harpercollins.com/9780061766084/change-by-design> (Accessed 13/4/13)

Bryson, D. (2007), 'Unwearables', *Artificial Intelligence & Society*, 22(1), pp. 25-35 [Document provided by author].

Bryson D. (2009) 'Designing smart clothing for the body'. In: McCann J, Bryson, D. (eds.) *Smart clothes and wearable technology*. Oxford, Cambridge, New Delhi: Woodhead Publishing Limited, chapter 5, pp. 95-106.

Buchenau, M. and Fulton Suri, J. (2000) 'Experiencing Prototyping', *DIS '00 Designing interactive systems 2000*, Brooklyn, New York, August 17-19, 2000 [Online]. Available at: http://www.ideo.com/images/uploads/news/pdfs/FultonSuriBuchenau-Experience_PrototypingACM_8-00.pdf (Accessed 12/5/13)

Candy, L. (2006) 'Practice Based Research: A Guide', Report from Creativity and Cognition Studios, University of Technology, Sydney [Online]. Available at: www.creativityandcognition.com/resources/PBR%20Guide-1.1-2006.pdf (Accessed: 22/7/13)

Candy, L. and Edmonds, E. A. (2010) 'The Role of the Artefact and Frameworks for Practice-based Research'. *The Routledge Companion to Research in the Arts*, M. Biggs and H. Larsson (eds), Routledge [Online]. Available at: http://www.researchgate.net/profile/Linda_Candy/publication/257944847_The_Role_of_the_Artefact_and_Frameworks_for_Practice-based_Research/links/00b7d5266bbd47e1e7000000.pdf. (Accessed 4/2/15)

Cassidy, T. (2011) 'The Moodboard Process Modeled and Understood as a Qualitative Design Research Tool', *Fashion Practice: The Journal of Design, Creative Process & the Fashion Industry*, 3(2), pp. 225-252.

Catrysse, M., Pirotte, F. and Puers, R. (2007) 'The use of electronics in medical textiles' in Van Langenhove, L., (ed.) *Smart textiles for medicine and healthcare: Materials, systems and applications*, Oxford: Woodhead Publishing, chapter 5, pp. 88-104.

Chang, A. (2005) 'Engineers are from Mars, Fashion designers are from Venus: Bridging the gap between two opposing industries', *Wearable Futures Conference University of Wales, Newport, 2005* [Online]. Available at: http://www.docstoc.com/docs/164623458/Engineers-Are-from-Mars_-Fashion-Designers-Are-from-Venus (Accessed 04/03/12)

Chapman, C., Sandbach, D., Hecht, S. and Colin, K. (2001) *Fabrications*. UK: Electrotexiles.

Chapman J. (2005) *Emotionally Durable Design: Objects, Experiences & Empathy*. London: Earthscan.

Chapman R., A. (2010) *Applications of Nonwovens in Technical Textiles*. Oxford, Cambridge, New Delhi: Woodhead Publishing.

Chiodo, J. D., Billet, E. H. and Harrison, D. J. (1999) 'Active disassembly using shape memory polymers for the mobile phone industry', *Proceeding of the 1999 IEEE International Symposium on Electronics and the Environment*, pp. 151–156 [Online]. Available at: <http://ieeexplore.ieee.org/xpl/articleDetails.jsp?arnumber=765867> (Accessed 18/11/11)

Cleland, I. (2012) *Investigation into the Application of Sensor Technologies within Smart Garments*. PhD thesis. University of Ulster [Online]. Available at: <http://ethos.bl.uk/OrderDetails.do?uin=uk.bl.ethos.592667> (Accessed: 14/1/15)

Cooper, A. (1999) *The Inmates are Running the Asylum*. Indianapolis: Macmillan Publishing. Courage, C. and Baxter, K. (2005) *Understanding your users*, San Francisco: Morgan Kaufmann Publishers Inc.

Coyle, S., Wu, Y., Lau, K. T., Brady, S., Wallace, G. and Diamond, D. (2007) 'Bio-sensing textiles - Wearable Chemical Biosensors for Health Monitoring', *4th International Workshop on Wearable and Implantable Body Sensor Networks (BSN 2007)*, IFMBE Proceedings, Volume 13, 2007, pp. 35-39 [Online]. Available at: https://www.researchgate.net/profile/Shirley_Coyle/publications?sorting=newest&page=4 (Accessed: 18/5/13)

- Coyle, S., Morris, D., Lau, K.-T., Di Francesco, F., Taccini, N., Trivella, M. G., Costanzo, D., Salvo, P., Porchet, J.-A. and Luprano, J. (2009) 'Textile sensors to measure sweat pH and sweat-rate during exercise', *Pervasive Health 2009*, 1-3 April 2009, London, UK [Online]. Available at: http://doras.dcu.ie/3636/1/Coyle_pervasive2009.pdf (Accessed: 21/1/14)
- Coyle, S., Lau, K. T., Moyna, N., O'Gorman, D., Diamond, D., Di Francesco, F., Costanzo, D., Salvo, P., Trivella, M. G., De Rossi, D. E., Taccini, N., Paradiso, R., Porchet, J.-A., Ridolfi, A., Luprano, J., Chuzel, C., Lanier, T., Revol-Cavalier, F., Schoumacker, S., Mourier, V., Chartier, I., Convert, R., De-Moncuit, H. and Bini, C. (2010) 'BIOTEX-Biosensing Textiles for Personalised Healthcare Management', *IEEE transactions on information technology in biomedicine*, 14(2), pp. 364-370 [Online]. Available at: http://www.academia.edu/1922554/BIOTEX_Biosensing_textiles_for_personalised_healthcare_management (Accessed: 18/5/13)
- Coyle, S. and Diamond, D. (2013) 'Medical applications of smart textiles'. In: Kirstein, T. (ed.) *Multidisciplinary know-how for smart-textiles developers*. Cambridge, Philadelphia, New Delhi: Woodhead Publishing Limited, chapter 15, pp. 420-443.
- Cross, N. (1982) 'Designerly ways of knowing', *Design Studies Journal*, 3(4), pp. 221-227 [Online]. Available at: oro.open.ac.uk/3281/1/Designerly_DisciplineScience.pdf (Accessed 27/3/12)
- Dias, T. (2013) 'Textiles with Electronic Functionality', *Sensors in Medicine Conference London, 2013* [Online]. Available at: www.sensor100.com/sensmed2013/t.dias.pdf (Accessed 27/5/15)
- Druss, B., Olfson M. and Pincus, H. (2002) 'The Most Expensive Medical Conditions in America'. *Health Affairs*, 21(4), pp. 105-111 [Online]. Available at: <https://hpi.georgetown.edu/agingsociety/pubhtml/backpain/backpain.html> (Accessed 19/3/12)
- Dunne, L. E. (2004) *The Design of Wearable Technology: Addressing the human-device interface through functional apparel design*. Master of Arts Thesis, Faculty of the Graduate School of Cornell University [Online]. Available at: <http://ecommons.cornell.edu/bitstream/1813/150/2/Lucy%20E%20Dunne-Masters%20Thesis.pdf> (Accessed: 16/12/11)
- Dunne, L. E., Ashdown, S. P. and Smyth, B., (2005) 'Expanding garment functionality through embedded electronic technology', *Journal of Textile and Apparel, Technology and Management*, 4(3) [Online]. Available at: https://www.researchgate.net/publication/228673324_Expanding_garment_functionality_through_embedded_electronic_technology (Accessed 19/12/11)
- Dunne, L. (2010) 'Smart Clothing in Practice: Key Design Barriers to Commercialization', *Fashion Practice: The Journal of Design, Creative Process & the Fashion Industry*, 2 (1), pp. 41-66(26).
- Frayling, C. (1993), 'Research in Art & Design', *Royal College of Art Research Papers*, 1(1) [Online]. Available at: <http://researchonline.rca.ac.uk/384/> (Accessed 23/4/15)
- Fuad-Luke A. (2009) *Design Activism: Beautiful Strangeness for a Sustainable World*. London: Earthscan.

Gallagher, M., Wysocki, C. J., Leyden, J. J., Spielman, A. J., Sun, X. and Preti, G. (2008) 'Analyses of volatile organic compounds from human skin', *British Journal of Dermatology*, 159(4), pp. 780-791 [Online]. Available at: <http://onlinelibrary.wiley.com/doi/10.1111/j.1365-2133.2008.08748.x/abstract> (Accessed 12/4/13)

Gemperle, F., Kasabach, C., Stivoric, J., Bauer, M. and Martin, R. (1998) 'Design for Wearability', *Proceedings of the 2nd IEEE International Symposium on Wearable Computers 1998*, pp. 116-122 [Online]. Available at: monet.cs.columbia.edu/courses/mobwear/resources/gemperle-iswc98.pdf (Accessed 19/3/13)

Ghosh, T.K., Dhawan, A. and Muth. J. F. (2006), 'Formation of electrical circuits in textile structures', in Mattila, H.R. (ed.) *Intelligent Textiles and Clothing*. Cambridge: Woodhead Publishing; Boca Raton, FL: CRC, chapter 14, pp. 239-282.

Goldsworthy, K. (2010) 'Resurfaced: an exploration of 'design for upcycling' through laser finishing for textiles', *Cutting Edge: Lasers and Creativity*, 4th November 2010, Loughborough College of Art & Design [Online]. Available at: www.cuttingedgesymposium.com/pdf/kate-goldsworthy-paper.pdf (Assessed: 10/7/14)

Gray, C. and Malins, J. (2004) *Visualizing research: a guide to the research process in art and design*. Aldershot: Ashgate.

Hansen Degn, A-L., Hansen M. and Jensen, H. T. (2011) *Future Textiles. Trends Inspiration Drivers & Barriers Smart textiles*. Herning: Knowledge Centre for Smart Textiles [Received on request from Poul-Erik Jørgensen at Knowledge Centre for Smart Textiles at VIA University College, Herning]

Ho J. and Intille S. (2005) 'Using context-aware computing to reduce the perceived burden of interruptions from mobile devices', *Proceedings of CHI 2005 Connect: Conference on Human Factors in Computing Systems*. New York, NY: ACM Press, 2005, pp. 909 – 918 [Online]. Available at: web.media.mit.edu/~intille/papers-files/HoIntille05.pdf (Accessed: 22/3/12)

Hurford, R. (2009) 'Types of smart clothes and wearable technology', in McCann, J. & Bryson, D. (eds), (2009) *Smart Clothes & Wearable Technology*, London: Woodhead Publishing Limited, pp. 25-43.

Kane, F. E. (2009) 'Nonwovens in Smart Clothes & Wearable Technologies', in *Smart Clothes & Wearable Technologies*, J.McCann and D.Bryson (eds), Cambridge: Woodhead Publishing Limited, chapter 8, pp. 156-182.

Kazani, I., Hertleer, C., De May, G., Schwarz, A., Guxho, G. and Van Langenhove, L. (2012) 'Electrical Conductive Textiles Obtained by Screen Printing', *Fibres & Textiles in Eastern Europe*, 20(1), pp. 57-62 [Online]. Available at: <http://biblio.ugent.be/publication/1996887/file/1996913> (Accessed: 10/12/14)

Kirstein, T., Tröster, G., Locher, I. and Küng, C. (2007) 'Wearable assistants for mobile health monitoring' in Van Langenhove, L., (ed.) *Smart textiles for medicine and healthcare: Materials, systems and applications*, Oxford: Woodhead Publishing Limited, chapter 13, pp. 253-275.

Köhler, A. R. (2008) *End-of-life implications of electronic textiles*. Assessment of a converging technology. Master of Science thesis. Lund University, Sweden [Online]. Available at: <http://lup.lub.lu.se/student-papers/record/1480555/file/1480556.pdf> (Accessed: 10/10/11)

Köhler, A. R. (2013) *Anticipatory Eco-Design Strategies for Smart Textiles Perspectives on environmental risk prevention in the development of an emerging technology*. PhD thesis. Delft University of Technology [Online]. Available at: https://www.researchgate.net/publication/256472264_Anticipatory_Eco-Design_Strategies_for_Smart_Textiles_Perspectives_on_environmental_risk_prevention_in_the_development_of_an_emerging_technology (Accessed: 26/5/15)

Köhler A. R. and Som C. (2005) 'Effects of Pervasive Computing on Sustainable Development', *Technology and Society Magazine*, IEEE, volume 24, issue 1, pp. 15-23 [Online]. Available at: http://d73753.u28.alsonetworks.com/technology_and_society/free_sample_article.asp?ArticleID=1 (Accessed: 2/10/12)

Köhler, A. R., Hilty, L. M and Bakker, C. A. (2011). 'Prospective Impacts of Electronic Textiles on Recycling and Disposal', *Journal of Industrial Ecology*, 15(4), pp. 496-511 [Online]. Available at: https://www.researchgate.net/publication/227733221_Prospective_Impacts_of_Electronic_Textiles_on_Recycling_and_Disposal (Accessed: 4/10/13)

Kolb, D. A. (1984) *Experiential Learning: experience as the source of learning and development*. Englewood Cliffs, NJ: Prentice Hall.

Langereis, G., De Voogd-Claessen, L., Spaepen, A., Siplia, A., Rotsch, C. and Linz, T. (2007) 'ConText: Contactless Sensors For Body Monitoring Incorporated In Textiles', *International Conference on Portable Information Devices*, 2007, Orlando, 25-29 May 2007 [Online]. Available at: http://ieeexplore.ieee.org/xpl/login.jsp?tp=&arnumber=4216927&url=http%3A%2F%2Fieeexplore.ieee.org%2Fxppls%2Fabs_all.jsp%3Farnumber%3D4216927 (Accessed 12/8/12)

Lee, S. (2005), *Fashioning the Future: Tomorrow's wardrobe*. UK: Thames & Hudson.

Leitner, C. (2005) *Paper Textiles*. London: A & C Black Publishers Ltd.

LeRouge, C., Ma, J., Sneha, S. and Tolle, K. (2013) 'User profiles and personas in the design and development of consumer health technologies', *International Journal of Medical Informatics*, 82(11), pp. 251-268 [Online]. Available at: <http://www.ncbi.nlm.nih.gov/pubmed/21481635> (Accessed: 27/3/15)

Lewis-Beck, M., Bryman, A. E. and Futing Liao, T. (2004) *The SAGE Encyclopedia of Social Science Research Methods*. London: Sage Publications.

Li, L., Au, W. M., Li, Y., Wan, K. M., Chung, W. Y. and Wong, K. S. (2009) 'A Novel Design Method for an Intelligent Clothing Based on garment Design and Knitting Technology' *Textile Research Journal*, 79, pp. 1670-1679 [Online]. Available at: <http://myweb.polyu.edu.hk> (Accessed: 9/4/15)

Linz, T., Gourmelon, L. and Langereis, G. (2006) 'Fully Integrated EKG Shirt based on Embroidered Electrical Interconnections with Conductive Yarn and Miniaturized Flexible Electronics.' *Proceedings of the International Workshop on Wearable and Implantable Body Sensor Networks (BSN'06)* [Online]. Available at: <http://venividiwiki.ee.virginia.edu/mediawiki/images/b/ba/Wear5.pdf> (Accessed: 9/12/14)

Linz, T. (2007) 'Enabling Micro System Technologies for Electronics in Textiles', paper presented at Concertation WS on EC-Funded Projects on Smart Fabrics and Interactive Textiles (SFIT) and Consultation on Future R & D Challenges and Opportunities, Brussels. [Online]. Available at: ftp://ftp.cordis.europa.eu/pub/ist/docs/mnd/torsten-linz-fraunhofer-izm-pa-sfit_en.pdf. (Accessed: 8/5/12)

Liu, H., Xiang, Y., Lu, Y. and Crooks, R. M. (2012) 'Aptamer-Based Origami Paper Analytical Device for Electrochemical Detection of Adenosine' *Angewandte Chemie International Edition*, 51(28), pp. 6925–6928 [Online]. Available at: <http://onlinelibrary.wiley.com/doi/10.1002/anie.201202929/abstract> (Accessed 28/5/14)

Lofthouse, V. A. and Lilley, D. (2006) 'What they really, really want: user centred research methods for design', *Proceedings of the International Design Conference, Design 2006*, 15-18 May, Dubrovnik [Online]. Available at: <https://dspace.lboro.ac.uk/dspace-jspui/handle/2134/2189> (Accessed: 7/11/12)

Malmivaara, M. (2009) 'The emergence of wearable computing'. In: McCann J, Bryson, D. (eds) *Smart Clothes and wearable technology*. Oxford, Cambridge, New Delhi: Woodhead Publishing Limited, chapter 1, pp. 3-23.

Martinez-Lozano Sinues, P., Kohler, M. and Zenobi, R. (2013) 'Human Breath Analysis May Support the Existence of Individual Metabolic Phenotypes', *PLOS ONE* Open Access journal, 8(4), e59909 [Online]. Available at: <http://www.plosone.org/article/info%3Adoi%2F10.1371%2Fjournal.pone.0059909> (Accessed: 7/3/14)

Mattila, H. (2001) 'Wearable technology for snow clothing'. In: Tao, X. M. (ed.) *Smart fibres, fabrics and clothing*. Cambridge: Woodhead Publishing Limited, chapter 14, pp. 246-252.

McCann, J. (2009) 'The garment design process for smart clothing; from fibre selection through to product launch'. In: McCann, J. and Bryson, D. (eds) *Smart clothes and wearable technology*. Cambridge: Woodhead Publishing Limited, chapter 4, pp. 70-94.

McCann, J. (2009a) 'End-user based design of innovative smart clothing'. In McCann, J. and Bryson, D. (eds) *Smart clothes & wearable technology*. Cambridge: Woodhead Publishing Limited, chapter 3, pp. 45-66.

McDonough, W. and Braungart, M. (2003), *Cradle-to-cradle: remaking the way we make things*. North Point Press, New York.

Miller, E. (1992) *Textiles: Properties and behaviour in clothing use*. London: B T Batsford Limited.

- Mishra, A., Greaves, R. and Massie, J. (2005) 'The Relevance of Sweat Testing for the Diagnosis of Cystic Fibrosis in the Genomic Era', *The Clinical Biochemist*, 26(4), pp. 135–153 [Online]. Available at: <http://www.ncbi.nlm.nih.gov/pmc/articles/PMC1320177> (Accessed 8/11/14)
- Morris, D., Coyle, S., Wu, Y., Lau, K.-T., Wallace, G. and Diamond, D. (2009) 'Bio-sensing textile based patch with integrated optical detection system for sweat monitoring', *Sensors and Actuators B: Chemical*, 139 (1), pp. 231-236 [Online]. Available at: <http://doras.dcu.ie/4566/> (Accessed 8/11/14)
- Norman, D. A. and Draper, S. W (1986) *User Centered System Design: New Perspectives on Human-computer Interaction*. Hillsdale, New Jersey, USA: L. Erlbaum Associates Inc.
- O'Reilly, K. (2008) 'Focus Groups and Group Discussion', *Key Concepts in Ethnography*. London: SAGE Publications, pp. 78-82 [Online]. Available at: http://www.credoreference.com/entry/sageuketh/focus_groups_and_group_discussion (Accessed: 15/2/13)
- Ossevoort, S. H. W. (2013) 'Improving the sustainability of smart textiles'. In: *Multidisciplinary know-how for smart-textiles developers*, Kirstein, T. (ed.), Cambridge: Woodhead Publishing Limited, chapter 14, pp. 399-419.
- Park, S. and Jayaraman, S. (2001) 'Adaptive and Responsive Textile Structures'. In: *Smart fibers, fabrics and clothing: Fundamentals and Applications*, Tao, X. M. (ed.), Cambridge: Woodhead Publishing Limited, chapter 13, pp. 226-245.
- Paroloa, C. and Merkoci, A. (2012) 'Paper-based nanobiosensors for diagnostics', *Chemical Society Reviews*, 2 (2013), pp. 450-457, received by email from author, May 14.
- Post, E. R., Orth, M., Russo, P. R. and Gershenfeld, N. (2000) 'E-broidery: Design and fabrication of textile based computing', *IBM SYSTEMS JOURNAL*, 39(3.4), pp. 840-860 [Online]. Available at: https://www.researchgate.net/publication/224101928_E-broidery_Design_and_fabrication_of_textile-based_computing (Accessed: 20/12/11)
- Pourdeyhimi B., Grant E. and J. M. Wilson (2006) 'Printing onto Nonwoven Conformal Fabrics using Conductive Inks and Intelligent Control', *National Textile Center Annual Report*, November 2006 [Online]. Available at: www.ntcresearch.org/pdf-rpts/AnRp06/F04-NS17-A6.pdf (Accessed: 10/12/14)
- Punch, K. F. (2014) *Introduction to Social Research: Quantitative and Qualitative Approaches*. London: SAGE Publications.
- Rehnby, W., Gustafsson, M. and Skrifvars, M. (2008) 'Coating of Textile Fabrics with Conductive Polymers for Smart Textile Applications', *Proceedings of Smart Textiles–Technology and Design*, Ambience 2008, Boras, Sweden, 2–3 June 2008, pp. 100–103 [Online]. Available at: <http://bada.hb.se/bitstream/2320/4110/2/RehnbyGustafssonSkrifvarsAmbience08.pdf>. (Accessed: 2/6/12)
- Rogers, E. M. (1962) *Diffusion of Innovations*. Glencoe: Free Press.
- Salvador, T., Bell, G. and Anderson, K. (1999) 'Design Ethnography', *Design Management Journal* 10(4.2) [Online]. Available at: <http://cleo.ics.uci.edu> (Accessed: 20/11/12)

Sandelowski, M. (1995) 'On the aesthetics of qualitative research', *Image: Journal of Nursing Scholarship*, 27(3), pp. 205-209 [Online]. Available at: <http://onlinelibrary.wiley.com/doi/10.1111/j.1547-5069.1995.tb00860.x/abstract> (Accessed: 20/1/15)

Schön, D. A. (1983) *The reflective practitioner: how professionals think in action*. New York: Basic Book.

Scrivener, S. (2000) 'Reflection in and on action and practice in creative-production doctoral projects in art and design', *Working Papers in Art and Design 1* [Online]. Available at: http://sitem.herts.ac.uk/artdes_research/papers/wpades/vol1/scrivener2.html (Accessed: 2/11/11)

Seago, A. and Dunne, A. (1997) 'New methodologies in Art and Design Research: The Object as Discourse', *Royal College of Art Research Papers*, 2(1) [Online]. Available at: <http://researchonline.rca.ac.uk/401/> (Accessed: 5/2/12)

Seymour, S. (2008) *Fashionable Technology: the intersection of design, fashion, science and technology*. Wien: Springer.

Seymour, S. (2010) *Functional Aesthetics: Visions in Fashionable Technology*. Wien: Springer.

Sherwin, C. (2000) *Innovative ecodesign: An exploratory and descriptive study of Industrial Design practice*, PhD Thesis. Cranfield University [Online]. Available at: <http://dspace.lib.cranfield.ac.uk/handle/1826/3543> (Accessed 20/11/12)

Shim, E. (2013) 'Smart surface treatments for textiles for protection'. IN: *Smart textiles for protection*, Chapman R. A. (ed.), Cambridge: Woodhead Publishing Limited, chapter 3, pp. 87-120.

Shirasu M. and Touhara, K. (2011) 'The scent of disease: volatile organic compounds of the human body related to disease and disorder', *The Journal of Biochemistry* [Online]. Available at: <http://jb.oxfordjournals.org/content/early/2011/07/19/jb.mvr090.abstract> (Accessed 13/2/14)

Steckl, A. J. (2013) 'Circuits on cellulose', *IEEE SPECTRUM*, 50(2), pp. 48-61 [Online]. Available at: www.nanolab.uc.edu/Publications/PDFfiles/400.pdf (Accessed: 19/12/14)

Stevens, A. (2007) *Adventures in EcoDesign of Electronic Products 1993-2007*. Delft: Delft University of Technology, Design for Sustainability Program [Online]. Available at: <http://repository.tudelft.nl/view/ir/uuid%3Ac7223473-bedb-4b01-a99e-b05865071acd/%20Editor:%20Ab%20Stevens,%20ISBN:%20978-90-5155-039-9> (Accessed: 28/5/15)

Strauss, A. and Corbin, J. (1998) *Basics of Qualitative Research*. Thousand Oaks, London, New Delhi: SAGE Publications.

Swallow, A. and Thompson, A. P. (2001) 'Sensory Fabric for ubiquitous interfaces', *International Journal of Human-Computer Interaction*, 13 (2), pp. 147-159 [Online]. <https://www.mendeley.com/research/sensory-fabric-ubiquitous-interfaces/> (Accessed: 8/12/11)

- Swan, M. (2012) 'Health 2050: The Realization of Personalized Medicine through Crowdsourcing, the Quantified Self, and the Participatory Biocitizen', *Journal of Personalised Medicine*, 2(3), pp. 93-118 [Online]. Available at: <http://www.mdpi.com/2075-4426/2/3/93> (Accessed: 15/3/14)
- Tao, X. M. (2001) 'Smart technology for textiles and clothing-introduction and overview'. In: Tao, X. M. (ed.) *Smart fibres, fabrics and clothing*. Cambridge: Woodhead Publishing Limited, chapter 1, pp. 1-5.
- Taelman J., Adriaensen, T., Van der Horst, C., Linz, T. and Spaepen, A. (2007) 'Textile Integrated Contactless EMG Sensing for Stress Analysis', *Conference Proceedings Annual International Conference of the IEEE Engineering in Medicine and Biology Society*, pp. 3966-3969 [Online]. Available at: https://www.researchgate.net/publication/5843860_Textile_integrated_contactless_EMG_sensing_for_stress_analysis (Accessed: 23/5/12)
- Thackara, J. (2001) 'The design challenge of pervasive computing', *Interactions*, Volume 8, Issue 3, May/June 2001, pp. 46-52 [Online]. Available at: www.cs.cmu.edu/afs/cs.cmu.edu/Web/People/jasonh/courses/ubicomp-sp2007/papers/08-thackara-design-challenge-pervasive.pdf (Accessed: 4/3/12)
- Thorpe, A. (2008) 'Design as Activism: A conceptual tool 2008', *Changing the Change: Design, Visions, Proposals and Tools*, Changing the Change conference, July 10-12 2008, Turin, Italy. Umberto Allemandi & C., Torino [Online]. Available at: <http://www.allemandi.com/ebook.php> (Accessed: 19/9/12)
- Timmins, M. (2009) 'Environmental and waste issues concerning the production of smart clothes and wearable technology'. In: McCann, J. and Bryson, D. (eds) *Smart clothes and wearable technology*. Oxford: Woodhead Publishing Limited, chapter 16, pp. 319-331.
- Tischner, U. and Charter, M. (2001) *Sustainable Solutions: Developing Products and Services for the Future*. Sheffield: Greenleaf-Publishing.
- Tischner U. and Hora, M. (2012) 'Sustainable electronic product design'. In: Goodship, V. and Stevels, A (eds) *Waste Electrical and Electronic Equipment (WEEE) Handbook*, chapter 19, pp. 405-439.
- Tremblay M., Hevner A. and Berndt D. (2010) 'Focus Groups for Artifact Refinement and Evaluation in Design Research', *Communications of the Association for Information Systems*, 26 (article 27), pp. 599-618 [Online]. Available at: <https://datapro.fiu.edu> (Accessed: 15/2/13)
- Van Langenhove, L. and Hertleer, C. (2004) 'Smart clothing: a new life', *International Journal of Clothing Science and Technology*, 16(1/2) [Online]. Available at: <http://www.emeraldinsight.com/doi/abs/10.1108/09556220410520360> (Accessed 13/3/12)
- Walker, S., (2006), *Sustainable by Design: Explorations in Theory & Practice*. London: Earthscan.
- Wang, B. L., Takigawa, T., Takeuchi, A., Yamasaki Y., Kataoka, H., Wang, D. H. and Ogino, K. (2007) 'Unmetabolized VOCs in urine as biomarkers of low level exposure in indoor environments', *Journal of Occupational Health*, 49(2), pp. 104-110 [Online]. Available at: <http://www.ncbi.nlm.nih.gov/pubmed/17429167> (Accessed: 8/9/13)

Weiser, M. (1991) 'The computer for the 21st century', *Scientific American*, 265(3), pp. 94-104, [Online]. Available at: <https://www.lri.fr/~mbl/Stanford/CS477/papers/Weiser-SciAm.pdf> (Accessed: 16/12/11)

Wooley, M. (2000) 'Making change: design, diversity and practice-related research', *Research into practice* conference proceedings. Hertford UK: University of Hertfordshire.

Yilmaz, T., Foster, R. and Hao, Y. (2010) 'Detecting Vital Signs with Wearable Wireless Sensors', *Sensors*, 10(12), pp. 10837-10862 [Online]. Available at: <http://www.mdpi.com/1424-8220/10/12/10837> (Accessed: 29/10/14)

Ying, M., Bonifas, A. P., Lu, N., Su, Y., Li, R. Cheng, H., Ameen, A., Huang, Y. and Rogers, J. A (2012) 'Silicon nanomembranes for fingertip electronics', *Nanotechnology*, 23(34) [Online]. Available at: <http://iopscience.iop.org/0957-4484/23/34/344004> (Accessed: 9/12/12)

Internet articles and reports

Ahadome, T. (2012) 'Wearable Technology-A global market overview', *ISM Research White Paper* [Online]. Available at: <http://in-medica.com/contact.php?paper=3> (Accessed: 19/10/12)

Alleyne, R. (2008) 'Marks & Spencer under fire for school blazer that hides iPod', the Telegraph, 15 August [Online]. Available at: <http://www.telegraph.co.uk/news/2563929/Marks-and-Spencer-under-fire-for-school-blazer-that-hides-iPod.html> (Accessed: 7/11/11)

ASTM (2012), *Smart Textile Applications 2012 workshop agenda*, ASTM International [Online]. Available at: http://www.astm.org/filtrexx40.cgi?-P+MAINCOMM+D13+-P+EVENT_ID+2112+-P+MEETING_ID+69902+-P+MEM_NUM++/usr6/htdocs/newpilot.com/MEETINGS/sympotherprinterinfo.frm (Accessed 4/3/12)

Barry, L. (2014) 'Nike gears up for manufacturing revolution', *Just-style online news, insight and research portal* [Online]. Available at: http://www.just-style.com/analysis/nike-gears-up-for-a-manufacturing-revolution_id121679.aspx (Accessed: 20/5/14)

Benito-Lopez, F. (2010) quoted by Coyle, C. in: 'Sweat Sensor has Athletes in a Lather', Sunday Times, 2 May [Online]. Available at: <http://www.sfi.ie/news-resources/science-in-the-news/sweat-sensor-has-athletes-in-a-lather.html> (Accessed: 10/5/12)

Berzowska, J. (2004) 'Intimate Electronics', *Wearable Computers, Electronic Textiles, and Reactive Fashion*, Horizon Zero issue 16: Wear [Online]. Available at: <http://www.horizonzero.ca/textsite/wear.php?is=16&file=4&tlang=0> (Accessed: 7/11/11)

Bruning, L. (no date) 'Needle Felting Conductive fabric' [Online]. Available at: <http://www.instructables.com/id/Needle-Felting-Conductive-Thread/> (Accessed: 12/9/12)

Canalys (2014) '1.6 million smart bands shipped in H2 2013', *press release* [Online]. Available at: <http://www.canalys.com/newsroom/16-million-smart-bands-shipped-h2-2013> (Accessed 14/2/14)

Crothers, B. (2014) 'Why wearable tech could pose health risks' [Online]. Available at: <http://www.foxnews.com/tech/2014/10/20/experts-why-wearable-tech-could-pose-health-risks/> (Accessed: 21/11/14)

CSEM (2010) 'Cluster of EC co-financed projects on Smart fabrics, interactive Textile' [Online]. Available at: <http://csnej106.csem.ch/sfit/> (Accessed: 21/2/12)

CSEM, (2010a) 'Swiss Technology Award 2010 - The Joint Venture of CSEM and SUI, SenseCore AG is named among the three finalists for the most prestigious award for technology in Switzerland' [Online]. Available at: <http://www.csem.ch/site/card.asp?pld=13160> (Accessed: 21/2/12)

Dalsgaard, C. and Sterrett, R. (2014) *White paper on smart textile garments and devices: a market overview of smart textile wearable technologies*. Aarhus: Ohmatex ApS. [Online]. Available at: <http://www.innovationintextiles.com/white-paper-market-opportunities-for-smart-textiles-2014/> (Accessed: 21/8/14)

Darmour, J. (2010) 'Personal Healthcare: understanding our need(s) for a new healthcare experience' [Online]. Available at: <http://www.artefactgroup.com/content/personal-healthcare-understanding-our-needs-for-a-new-healthcare-experience/> (Accessed 15/3/13)

Dembosky, A. (2011) 'Invasion of the body hackers' [Online]. Available at: <http://www.ft.com/cms/s/2/3ccb11a0-923b-11e0-9e00-00144feab49a.html#axzz2WqTuoGME> (Accessed 8/8/11)

Dolan, B. (2013) 'Digital health sensing clothes are next in wearables' [Online]. Available at: <http://mobihealthnews.com/23227/digital-health-sensing-clothes-are-next-in-wearables/> (Accessed 21/5/15)

European Commission (no date) *Ecodesign brochure* [Online]. Available at: http://ec.europa.eu/enterprise/policies/sustainable-business/ecodesign/files/brochure_ecodesign_en.pdf (Accessed: 10/4/12)

ETH (2010) 'Woven electronics' [Online]. Available at: http://www.ethlife.ethz.ch/archive_articles/100701_smart_e_textilien_per/index_EN (Accessed: 3/4/12)

FDA (2012) *Regulatory Information* [Online]. Available at: <http://www.fda.gov/RegulatoryInformation/Legislation/FederalFoodDrugandCosmeticActFDCAct/FDCActChaptersandIShortTitleandDefinitions/ucm086297.htm> (Accessed 8/10/14)

Freiburger Appell (no date) *Internationaler Ärzteappell 2012* [Online]. Available at: <http://freiburger-appell-2012.info/de/home.php> (Accessed 18/11/13)

Friends of the Earth Europe (2013) 'Less is more: Resource efficiency through waste collection, recycling and reuse of aluminium, cotton and lithium in Europe' [Online]. Available at: <http://www.foeeurope.org/less-more-140213> (Accessed 21/4/14)

Fuller, D. (2014) 'HELLO? Sweat and a Smartphone Could Become The Hot New Health Screening' [Online]. Available at: <http://www.uc.edu/news/NR.aspx?id=20677> (Accessed 21/11/14)

- Goetz, T. (2008) 'Decision Tree' [Online]. Available at: <http://www.thomasgoetz.com/blog/2008/12/introducing-the-decision-tree> (Accessed 30/9/13)
- Halpin, H. A., Morales-Suárez-Varela M. M and Martin-Moreno, J. M. (2010) 'Chronic Disease Prevention and the New Public Health'. *Public Health Reviews* [Online]. Available at: <http://www.publichealthreviews.eu/show/f/24> (Accessed 23/4/15)
- Harrop, P., Das, R., and Chansin, G. (2014) 'Wearable Technology 2014-2024: Technologies, Markets, Forecasts' [Online]. Available at: <http://www.idtechex.com/research/reports/wearable-technology-2014-2024-technologies-markets-forecasts-000379.asp> (Assessed: 10/8/14)
- Havas Worldwide, (2012) *Havas PR Prosumer Report: 'My Body, Myself, Our Problem: Health and Wellness in Modern Times'* [Online]. Available at: <http://www.prosumer-report.com/blog/download-health-and-wellness-prosumer-report/> (Accessed: 12/8/14)
- Health Research Institute (2014) 'PwC's Health Research Institute Issues Report Shows Next Few Years Will be Crucial for Health Systems to Implement Consumer Friendly Technology' [Online]. Available at: <http://www.pwc.com/us/en/press-releases/2014/pwc-hri-report-consumer-friendly-technology.jhtml> (Accessed: 12/3/15)
- Herz, J. C. (2014) 'Wearables are totally failing the people who need them most' [Online]. Available at: <http://www.wired.com/2014/11/where-fitness-trackers-fail/> (Accessed: 11/6/14)
- Horrigan, J. (2009) 'The Mobile Difference' *Pew Internet & American Life Project Report* [Online]. Available at: <http://www.pewinternet.org/2009/03/25/the-mobile-difference/> (Accessed 12/1/14)
- Ikram, I. and Hashin, A. (2002) 'Natural Rubber Biodegradation in Soil in Relation to the Waste Disposal of Used Latex Products' [Online]. Available at: <http://www.rubbernews.com/article/20020101/DATA/301019985/natural-rubber-biodegradation-in-soil-in-relation-to-the-waste> (Accessed: 20/2/15)
- IMS Research (2012) 'Wearable Technology Innovation to Drive Market Growth' [Online]. Available at: http://imsresearch.com/news-events/press-template.php?pr_id=3059 (Accessed: 6/1/12)
- Jacobs School of Engineering (2011) 'Flexible, Printable Sensors Detect Underwater Hazards', *press release* [Online]. Available at: http://www.jacobsschool.ucsd.edu/news/news_releases/release.sfe?id=1093 (Accessed: 26/7/12)
- Jacobsen, V. B. (2011) 'What type of tech user are you?' [Online]. Available at: <http://www.pcmag.com/article2/0,2817,2387284,00.asp> (Accessed: 12/1/14)
- Jensen, G., Caterbow, A., Gabizon, S., Wurzbacher, K., Oda, Y., Doszhanova, E., Speranskaya, O. and Romano, D. (2013) 'NCDs and environmental determinants' [Online]. Available at: www.sustainlabour.org/documentos/NDCfinalight_2082013.pdf (Accessed: 7/12/13)

Juniper Research (2014) 'Smart Wearables Market to Generate \$53bn Hardware Revenues by 2019', *press release* [Online]. Available at: [http://www.juniperresearch.com/press/press-releases/smart-wearables-market-to-generate-\\$53bn-hardware](http://www.juniperresearch.com/press/press-releases/smart-wearables-market-to-generate-$53bn-hardware) (Accessed: 10/10/14)

Kettley, S. (2013) 'aeolia' [Online]. Available at: <http://sarahkettleydesign.co.uk/2013/02/20/aeolia/> (Accessed: 8/10/13)

Kobori, M. (2010), *My Beautiful Laundry* [Online]. Available at: http://www.huffingtonpost.com/michael-kobori/my-beautiful-laundry_b_619882.html (Accessed: 12/4/11)

Köhler, A. R (2011) *LCA to go tool* [Online]. Available at: <http://www.lca2go.eu/news-l2-content/19.htm> (Accessed: 7/9/13)

Lamontagne, V. (2011) 'Christian Dils & Manuel Seckel Interview' [Online]. Available at: <http://fashioningtech.com/profiles/blogs/christian-dils-amp-manuel> (Accessed: 8/3/14)

Lanxon, N. (2014) 'Google developing 'smart' contact lens to monitor blood sugar levels for diabetics' [Online]. Available at: <http://www.wired.co.uk/news/archive/2014-01/17/google-contact-lens> (Accessed: 18/2/14)

Ledger, D. (2014) 'Inside Wearables' *white paper* [Online]. Available at: <http://endeavourpartners.net/white-papers/> (Accessed: 23/10/14)

Lim, Y. (no date) 'FELT-ME' [Online]. Available at: <http://monograph.io/ylim/felt-me> (Accessed: 11/8/13)

Lombardi, E. (2006) quoted by West L. in: 'Zero Waste Starts with Responsible Design' [Online]. Available at: http://environment.about.com/od/greenlivingdesign/a/zero_waste.htm (Accessed 14/1/12)

Luprano, J. (2008), cited in 'Smart Clothes: Textiles that track your health' [Online]. Available at: <http://www.sciencedaily.com/releases/2008/03/080329121141.htm> (Accessed 30/12/14)

Mautone, S. (2014) 'Top 10 Form Factors of Wearable Technology' [Online]. Available at: <https://www.beaconreader.com/steven-mautone/top-10-wearable-form-factors> (Accessed 2/4/14)

Malik Chua, J. (2010) 'Smart Textile Shirt Protects Baseball Pitchers From Elbow Injuries' [Online]. Available at: <http://www.ecouterre.com/smart-textile-shirt-protects-baseball-pitchers-from-elbow-injuries/> (Accessed 17/6/12)

McDonald, C. (2014) 'What can be defined as wearable tech?' [Online]. Available at: <http://www.computerweekly.com/blogs/inspect-a-gadget/2014/12/what-can-be-defined-as-wearable-tech.html> (Accessed 7/2/15)

National Physical Laboratory (2013) 'Smart textiles-the answer for wearable electronics?' [Online]. Available at: <http://www.npl.co.uk/news/smart-textiles-the-answer-for-wearable-electronics> (Accessed 7/12/14)

Neidlinger, K. (2013) 'GER: Galvanic Extimacy Responder Mood Sweater' [Online]. Available at: <http://fashioningtech.com/profiles/blogs/ger-galvanic-extimacy> (Accessed 7/12/13)

Newcastle University (no date), definition of 'data' [Online]. Available at: <https://research.ncl.ac.uk/rdm/rdmncl/whatdoyoumeanbydata/> (Accessed: 14/1/15)

Nottingham Trent University (2013) 'Washable, wearable computers to become the next generation of advanced textiles' [Online]. Available at: http://www.ntu.ac.uk/apps/news/134741-15/Washable_wearable_computers_to_become_the_next_generation_of_advanced_textiles.aspx (Accessed: 6/2/13)

Nottingham Trent University, (2015) 'Nottingham Trent University shares in £20 million to manufacture fibre of the future' [Online]. Available at: [http://www.ntu.ac.uk/apps/news/168226-15/Nottingham Trent University shares in £20 million to manufacture fibre of the future.aspx](http://www.ntu.ac.uk/apps/news/168226-15/Nottingham_Trent_University_shares_in_£20_million_to_manufacture_fibre_of_the_future.aspx) (Accessed: 6/7/15)

Ouyang, B. (2014) 'ZIO Wireless Patch May Be Better Option Than Holter Monitors for Cardiac Arrhythmia Diagnosis' [Online]. Available at: <http://www.medgadget.com/2014/01/zio-wireless-patch-may-be-better-option-than-holter-monitors-for-cardiac-arrhythmia-diagnosis.html> (Accessed: 6/3/14)

Oxford English Dictionary Online¹, definition of 'research' [Online]. Available at: <http://www.oxforddictionaries.com/definition/english/research> (Accessed: 14/1/15)

Oxford English Dictionary Online², definition of 'artefact' [Online]. Available at: <http://www.oxforddictionaries.com/definition/english/artefact> (Accessed: 14/1/15)

Oxford English Dictionary Online³, definition of 'data' [Online]. Available at: <http://www.oxforddictionaries.com/definition/english/data> (Accessed: 14/1/15)

Parliamentary Office of Science & Technology (2008) *postnote: Smart Materials and Systems* [Online]. Available at: www.parliament.uk/briefing-papers/POST-PN-299.pdf (Accessed: 10/1/12)

Peek, N. (no date) 'Lasercut Stretchy Conductive Fabric Traces' [Online]. Available at: <http://www.instructables.com/id/Lasercut-Stretchy-Conductive-Fabric-Traces/> (Accessed: 18/3/12)

PRLog (2015) 'SQUID Wristband - Changing The Way People Charge Small Electronics', *press release* [Online]. Available at: <http://www.prlog.org/12444561-squid-wristband-changing-the-way-people-charge-small-electronics.html> (Accessed: 29/4/15)

ProeTEX (2009) 'ProeTEX Learning about Smart Textiles' [Online]. Available at: http://www.proetex.org/final%20proetex%20learning/learning_tool.htm (Accessed: 17/3/12)

ProeTEX (2009a) 'Firefighters and Civil Emergency Workers' [Online]. Available at: <http://www.proetex.org/final%20proetex%20learning/firefighters.htm> (Accessed: 2/4/12)

PRWeb (2013) 'Wearable Technology Market is Expected to Reach USD 5.8 Billion in 2018' [Online]. Available at: <http://www.prweb.com/releases/2013/6/prweb10830585.htm> (Accessed: 22/6/13)

Salber, P. (2014) 'Cyrca Health: A Wearable, Social Breast Cancer Screening Bra' [Online]. Available at: <http://thedoctorweighsin.com/cyrca-health-wearable-social-breast-cancer-screening-bra/> (Accessed: 21/8/14)

www.sciencedaily.com (2008) 'Smart Fabrics Make (Medical) Clothing' [Online]. Available at: <http://www.sciencedaily.com/releases/2008/10/081021190640.htm> (Accessed 24/4/12)

Sherwin, C. (2012) 'Embedding sustainability in all design' [Online]. Available at: <http://www.guardian.co.uk/sustainable-business/blog/embedding-sustainability-design-future?INTCMP=ILCNETTXT3487> (Accessed 30/11/12)

Textiles Intelligence (2012) 'The market for smart textiles and wearable technology is set for rapid growth' [Online]. Available at: <http://www.textilesintelligence.com/til/press.cfm?prid=448> (Accessed: 4/3/12)

Tucker, P. (2007) 'Smart fashion: The Digitally Enhanced Wardrobe Archives', *The Futurist*, 41(5) [Online]. Available at: <http://www.wfs.org/Sept-Oct07%20files/Visions.htm> (Accessed: 20/1/12)

UNEP, (no date), 'E-Waste Management' [Online]. Available at: <http://www.unep.org/gpwm/FocalAreas/E-WasteManagement/tabid/56458/Default.aspx> (Assessed: 12/1/13)

The University of Aberdeen (2014) 'Research Excellence Framework 2014' [Online]. Available at: <https://www.abdn.ac.uk/staffnet/research/research-excellence-framework-ref-305.php> (Assessed: 12/7/15)

University of Bath (no date) 'CLEVER Closed Loop Emotionally Valuable E-waste Recovery' [Online]. Available at: <http://www.bath.ac.uk/csct/research/projects/20130318-clever.html> (Assessed: 14/3/15)

United Nations (2011) 'Non-Communicable Diseases Deemed Development Challenge of 'Epidemic Proportions' in Political Declaration Adopted During Landmark General Assembly Summit', *United Nations sixty-sixth General Assembly Summit* [Online]. Available at: <http://www.un.org/press/en/2011/ga11138.doc.htm> (Assessed: 4/12/12)

US Department of State (2011) 'Addressing the Challenges of Non-communicable Diseases: Environmental Risk Factors' [Online]. Available at: <http://www.state.gov/p/io/rls/fs/172601.htm> (Accessed: 4/12/12)

US Environmental Protection Agency (1991) 'Risk Assessment for Toxic Air Pollutants: A Citizen's Guide' [Online]. Available at: http://www.epa.gov/airquality/air_risc/3_90_024.html (Accessed 2/12/12)

Walker, S. (2013) 'Wearable Technology-Market Assessment' *IHS White Paper* [Online]. Available at: www.ihs.com/pdfs/Wearable-Technology-sep-2013.pdf (Accessed 30/1/15)

Wayne State University (no date) 'Intelligent textiles' [Online]. Available at: <http://www.ece.eng.wayne.edu/~yxu/doc/researches/Intelligent%20textiles.htm> (Accessed: 22/3/15)

Webster, D. (2013) quoted in Dick-Agnew, 'IDEO's David Webster on Healthcare Design' [Online]. Available at: <http://www.azuremagazine.com/article/ideos-david-webster-on-healthcare-design/?view=desktop> (Accessed: 22/9/13)

Wolf, G. (2011) *Our Three Prime Questions* [Online]. Available at: <http://quantifiedself.com/2011/09/our-three-prime-questions/> (Accessed: 12/4/13)

World Health Organization (2014) 'Electromagnetic fields and public health: mobile phones', *fact sheet Nr. 193* [Online]. Available at: <http://www.who.int/mediacentre/factsheets/fs193/en/> (Accessed: 8/11/14)

WRAP (2014) *Sustainable Clothing Action Plan Knowledge Hub: Design for end-of-life* [Online]. Available at: <http://ckh.wrap.org.uk/endOfLife/designForEndOfLife?breadcrumb=Explore+by%3A+Processes+Step> (Accessed: 20/3/14)

WRAP (2014a) *Sustainable Clothing Action Plan Knowledge Hub: Process map* [Online]. Available at: <http://ckh.wrap.org.uk/clothingKnowledgeHub/processStep> (Accessed: 20/3/14)

Zyga, L. (2013), 'Inkjet-printed graphene electrodes may lead to low-cost, large-area, possibly foldable devices' [Online]. Available at: <http://phys.org/news/2013-04-inkjet-printed-graphene-electrodes-low-cost-large-area.html> (Accessed: 20/5/13)

Conference presentations and lectures

Burr, S., (2012) 'Macro Trends That Impact Wearables', *Smart Fabric Conference 2012*, Miami, 18-19 April [published digitally for delegates only].

Chapman, J. (2012) 'Rethinking Good Design in an Unsustainable Age', keynote presentation at TFRC/ TED *Perspectives on Sustainable Design* lecture at Central Saint Martins College of Art & Design, London, 6 February.

Curran, J. (2012) 'Design Ethnography', *SKIP lectures* at Royal College of Art, London, 11 November.

Jones, G. (2014) *Active Tracking debate*, Wearable Technology Conference London 2014, 19 March.

Lukowicz, P. (2012) 'Wearable Computing: From cyborgs to smartphones and back', *Wearable Technology Conference Munich 2012*, 30 January.

Moehring, U. (2012) 'Textile-based and Textile-integrated Sensor and Actuator Technologies-A Challenge', *Smart Fabric Conference 2012*, Miami, 18-19 April [published digitally for delegates only].

Prahl, A. (2013) 'Wearable bio-sensing for wellbeing: A material-driven design exploration', *LCF Textiles Symposium 2013: Connecting with Textiles*, London, 11 July.
<http://newsevents.arts.ac.uk/event/lcf-textiles-symposium-2013/>

Prahl, A. (2013a) 'Wearable e-noses for health & wellbeing: Exploration of a real user need as part of the design process', *Wearable Futures Conference Ravensbourne*, London, 11 December. <http://www.wearablefutures.co/speakers/anne-prahl/>

Prahl (2013b) 'Design for wellbeing: Exploring future opportunities for wearable e-noses', poster presentation at *Habit(at) Field Day* Centre for Sustainable Fashion, London, 3 December.

Prahl, A. (2014) 'A trend perspective: Designing out waste', *webinar for Youth Fashion Summit 2014*, Nordic Fashion Association [Online]. Available at:
<https://vimeo.com/87607213> (Accessed: 18/2/15)

Prahl, A. (2014a) 'Wearable Sensing for Preventative Health: A material-driven design exploration', *Transition: Re-thinking Textiles and Surfaces* conference at University of Huddersfield, November 2014 [published digitally for delegates only].
<https://www.hud.ac.uk/schools/artdesignandarchitecture/events/transition/#Programme>
(Track B: Sustainable Futures)

Scott, J. L. (2014) 'Skeleton-Material for Triggered Disassembly and Organs-Recovery of High Value Materials', *CLEVER Symposium*, London, 20 May.

Vanfleteren, J. (2012) 'Stretchable Electronics for Smart Textiles', *Smart Textiles meet Organic Electronics seminar*, Ghent University, 25 April [published digitally for delegates only].

Windmiller, J. (2013) 'Printed Bioelectronics for Textile and Epidermal Integration', presentation at *Smart Fabric Conference 2013*, San Francisco, 24-25 April [published digitally for delegates only].

Zeagler, C. (2012) 'How to promote the Implementation of Electronic Textile Interfaces within the Fashion Industry', presentation at *Smart Fabric Conference 2012*, Miami, 18-19 April [published digitally for delegates only].

Primary sources

Prahl, A. (2012) 'Wearable Technology: Issues and challenges across the entire lifecycle', *primary research document* (Appendix A).

QSer workshop participant (2014), quote during workshop 1, London College of Fashion, 4 December.

Additional Internet resources and references

All links were checked on 12 August 2015.

Chapter 2

- 2.1A <http://www.sciencedaily.com/releases/2008/07/080708110517.htm>
- 2.1B http://www.jacobsschool.ucsd.edu/news/news_releases/release-min.sfe?id=958
- 2.1C <http://www.frti.ch/en/home.html>
- 2.1D http://cordis.europa.eu/result/rcn/85863_en.html
- 2.1E <http://www.gizmag.com/adidas-launches-the-intelligent-running-shoe/2810/>
- 2.1F http://www.niehs.nih.gov/funding/challenges/myair_myhealth/
- 2.1G http://news.illinois.edu/news/14/0403microfluidics_JohnRogers.html
- 2.1H <http://www.ukplasticelectronics.com/plastic-electronics-how-they-could-change-consumer-technology/>
- 2.1I http://www.gla.ac.uk/news/archiveofnews/2014/may/headline_328014_en.html
- 2.1J www.rogers.matse.illinois.edu
- 2.1K <http://www.mc10inc.com/>
- 2.1L <http://electrozyme.com/>
- 2.1M <http://www.nanolab.uc.edu/>
- 2.1N <http://powercoatpaper.com/>
- 2.1O <http://www.gtresearchnews.gatech.edu/low-cost-paper-based-sensor/>
- 2.1P <http://cutecircuit.com/the-hug-shirt/>
- 2.1Q http://www.design.philips.com/philips/sites/philipsdesign/about/design/designportfolio/design_futures/dresses.page
- 2.1R <http://ldt.stanford.edu/~jeepark/jeepark+portfolio/cs147hw8jeepark.html>
- 2.1S <http://vivonoetics.com/products/sensors/lifeshirt/>
- 2.1T <http://www.numetrex.com/>
- 2.1U <http://www.moticon.de/>
- 2.1V <http://electrozyme.com/?team=joshua-windmiller>
- 2.1W <http://quantifiedself.com/about/>
- 2.1X <http://www.tfrc.org.uk/research/scentsory-design/>
- 2.1Y <http://www.talk2myshirt.com/blog/archives/955>
- 2.1Z <http://www.sensium-healthcare.com/sensiumvitals%C2%AE#.VWs3YUT8dLo>
- 2.2A <https://en.wikipedia.org/wiki/Hypercolor>
- 2.2B <http://www.talk2myshirt.com/blog/archives/873>
- 2.2C <http://www.squidlondon.com/>
- 2.2D <http://ns.umich.edu/new/releases/20266-nerve-gas-litmus-test-could-sense-airborne-chemical-weapons>
- 2.2E http://news.utexas.edu/2012/03/08/origami_malaria_hiv
- 2.2F <http://gmwgroup.harvard.edu/research/index.php?page=24>

Chapter 3

- ^{3A} <http://www.apollon.uio.no/english/articles/2011/lifescience-sweat.html>
- ^{3B} <http://newsoffice.mit.edu/2012/seizure-wrist-sensor-0427>
- ^{3C} <http://freiburger-appell-2012.info/en/home.php>
- ^{3D} www.tawkon.com
- ^{3E} <http://v2.nl/lab/blog/e-textile-waste>
- ^{3F} <http://www.kobakant.at/DIY/?p=3709>
- ^{3G} <http://www.lca2go.eu/>
- ^{3H} www.dfa.org
- ^{3I} <http://www.fuseproject.com/>
- ^{3J} <http://misfit.com/products/swarovski-shine>
- ^{3K} <http://www.moma.org/collection/artists/22583?locale=en>

Chapter 4

- ^{4A} <http://www.ref.ac.uk/>
- ^{4B} <http://www.designcouncil.org.uk/news-opinion/design-process-what-double-diamond>
- ^{4C} <http://www.smartfabricsconference.com/>
- ^{4D} <http://skip.rca.ac.uk/about-skip/>
- ^{4E} <http://www.lancaster.ac.uk/lica/people/stuart-walker>

Chapter 5

- ^{5A} <http://www.wired.com/2012/10/one-moment-01m/>
- ^{5B} <http://www.mindsetonline.co.uk/Catalogue/ProductDetail/rubber-latex?productID=7dae4016-509a-4e1d-bdb1-48b471a32bb3&catalogueLevelItemID=00000000-0000-0000-0000-000000000000>
- ^{5C} <http://www.bareconductive.com/shop/electric-paint-10ml/>
- ^{5D} <http://members.shaw.ca/ubik/thread/order.html>
- ^{5E} <https://www.animagic.com/examples/example13.php>
- ^{5F} <http://www.mindsetonline.co.uk/Catalogue/ProductDetail/thermochromic-pigments?productID=f5b261be-6a9d-4262-a436-20320965b12a&catalogueLevelItemID=931c9c38-7585-4c65-afd9-05bfb3d75626>
- ^{5G} <http://www.mdreams.com.sg/melflex/>
- ^{5H} <http://www.prochima.it/index.html>

Chapter 6

- ^{6A} <http://newsevents.arts.ac.uk/11545/trash-fashion-designing-out-waste/>
- ^{6B} <http://www.biocouture.co.uk/>
- ^{6C} www.launch.org
- ^{6D} <http://www.nikeresponsibility.com/infographics/materials/>
- ^{6E} <http://blogs.arts.ac.uk/fashion/2012/05/28/welcome-nike/>

- ^{6F} <http://www.c2ccertified.org/innovation-stories/puma>
- ^{6G} <http://www.teijin.com/solutions/ecocircle/>
- ^{6H} http://news.illinois.edu/news/15/0521self_destruct_ScottWhite_JohnRogers.html
- ^{6I} <http://www.wgsn.com>
- ^{6J} <http://phys.org/news/2013-03-biodegradable-nappies-recycled-cardboard.html>
- ^{6K} <http://www.gosee.us/news/art/modemuseum-antwerpen-paper-fashion-exhibition-with-walter-van-beirendonck-dirk-van-saene-jum-nakao-issey-miyake-7024>
- ^{6L} <http://www.permaset.com.au/>
- ^{6M} <http://bioalloy.org/micro-be>
- ^{6N} <http://www.fabricanltd.com/>

Chapter 7

- ^{7A} <http://mobihealthnews.com/18075/proteus-gains-de-novo-fda-clearance-for-ingestible-biomedical-sensor/>
- ^{7B} http://www.mdpi.com/journal/sensors/special_issues/implantable-sensors
- ^{7C} <http://www.geglobalresearch.com/blog/health-information-can-pore-right>
- ^{7D} http://www.electronicproducts.com/Sensors_and_Transducers/Sensors/P_F_Sensors_their_future_and_challenges.aspx
- ^{7E} http://www.envirotech-online.com/news/air-monitoring/6/breaking_news/introducing_wepo_2015s_innovative_wearable_air_pollution_sensor/33052/
- ^{7F} <http://joinclarity.io/index.html>
- ^{7G} <http://estimote.com/>

Chapter 8

- ^{8A} <http://quantifiedself.com/>
- ^{8B} <http://www.londonair.org.uk/london/asp/iPhone/>
- ^{8C} <http://www.mindbloom.com/juice>
- ^{8D} <http://expereal.com>
- ^{8E} <http://www.azumio.com/>
- ^{8F} <http://runkeeper.com/>

Chapter 10

- ^{10A} <http://www.adhesivesresearch.com/>
- ^{10B} <http://spectrum.ieee.org/biomedical/diagnostics/sweat-sensors-will-change-how-wearables-track-your-health>
- ^{10C} <http://medcitynews.com/2014/09/electrozymes-metabolism-monitoring-temp-tattoos-backed-mark-cuban/>
- ^{10D} <http://www.insidescience.org/content/hi-tech-tattoo-your-workouts/1557>

^{10E} <http://www.theguardian.com/sustainable-business/sustainable-fashion-blog/fashion-technology-renewable-energy-solar-charge-smartphone>

^{10F} <https://www.kickstarter.com/projects/1071086547/ampy-power-your-devices-from-your-motion>

^{10G} <http://www.newswise.com/articles/new-nanotechnology-converts-heat-into-power-when-it-s-needed-most>

^{10H} <http://www.rsc.org/chemistryworld/2013/06/biofuel-cell-tattoo-sweat-health>

Conferences and events attended

Wearable Technologies Conference, Munich, January 2012
(Reported on event for WGSN)

TFRC/ TED *Perspectives on Sustainable Design* lecture, Central Saint Martins College of Art & Design, London, February 2012

Future Human: Smart Self, London, March 2012

Future Fibres, Fabrics & Finishes, London College of Fashion, April 2012

Smart Fabrics Conference 2012, Miami, April 2012 (Reported on event for WGSN)

Smart Textiles meet Organic Electronics, Ghent University, April 2012

BSN 2012, 9th International Conference on Wearable and Implantable Body Sensor Networks, London, May 2012

Copenhagen Pre-Fashion Summit, Copenhagen, May 2012 (Workshop facilitator: 'Design for sustainable consumption' on behalf of WGSN)

Copenhagen Fashion Summit, Copenhagen, May 2012 (Speaker: 'Design for sustainable consumption' and reported on event for WGSN)

Sustainable Clothing Action Plan (SCAP) Annual conference, London, July 2012 (Speaker: 'Challenging our perceptions of dirt...or how to create low-impact laundry trends')

Quantified Self London Show & Tell Meetups, London, August 2012-February 2014

Future Human: Body Hacking, London, September 2012

SKIP workshop: Design Ethnography, Royal College of Art, London, November 2012

Smart Fabrics Conference 2013, San Francisco, April 2013

Digital Fashion Conference, London College of Fashion, May 2013

SKIP workshop: Writing Design, Royal College of Art, London, June 2013

SKIP Summer School: Inclusive Socially Responsive Design, London and Kingston, July 2013

LCF Textiles Symposium 2013: Connecting with Textiles, July 2013 (Presented paper: 'Wearable bio-sensing for wellbeing: A material-driven design exploration')

Habit(at) Field Day Centre for Sustainable Fashion, London College of Fashion, December 2013 (Presented poster: 'Design for wellbeing: Exploring future opportunities for wearable e-noses')

Wearable Futures Conference Ravensbourne, London, December 2013 (Presented paper: 'Wearable e-noses for health & wellbeing: Exploration of a real user need as part of the design process')

Wearable Technology Conference London, March 2014

Printed Electronics Conference & Tradeshow, Berlin, April 2014

CLEVER Symposium, London, May 2014

PhD by Design Conference, Goldsmiths, University of London, November 2014

Transition: Re-thinking Textiles and Surfaces Conference, University of Huddersfield, November 2014 (Presented paper: 'Wearable Sensing for Preventative Health: A material-driven design exploration')

List of figures and sources

All links checked 14 August 2015

Chapter 1

Fig 1.1: Research methodology stages, Prael (2015)

Chapter 2

Fig 2.1: Three types of electronic wearable sensors diagram, Prael (2015)

Fig. 2.2: Knitted electrically active structure (2013):

www.sensor100.com/sensmed2013/t.dias.pdf

Fig. 2.3: Aeolia Cello stretch sensor, 2010:

<https://spinhandspun.wordpress.com/tag/nigel-marshall/>

Fig. 2.4: Numetrex knitted sensor close-up (2008):

<http://www.textronicsinc.com/press/2008/textronics-inc-receives-fda-clearance-on-textile-electrode>

Fig. 2.5: Pressure sensitive 'Smart Sock' prototype (2012):

<http://www.alpha-fit.de/en/products/smartsock.html>

Fig. 2.6: Woven temperature sensor ETH Zurich:

<http://www.ife.ee.ethz.ch/research/groups/PlasticElectronics/integration>

Fig. 2.7: Needle-felted touch sensor: <https://www.adafruit.com/products/1088>

Fig. 2.8: Needle-felted motion sensor (2012): <http://newtextiles.media.mit.edu/?p=864>

Fig. 2.9: Printed chemical sensors (2010):

http://www.just-style.com/the-just-style-blog/smart-underwear-could-save-lives_id1839.aspx

Fig. 2.10: Electrode sensors printed on neoprene (2011):

<http://ucsdnews.ucsd.edu/archive/newsrel/general/20110707UnderwaterSensors.as>

Fig 2.11: Stitched stroke sensor: <http://www.kobakant.at/DIY/?p=792>

Fig. 2.12: Embroidered sensor, image taken from:

http://www.izm.fraunhofer.de/content/dam/izm/en/documents/Abteilungen/System_Integration_Interconnection_Technologies/TexLab/Context.pdf.

Fig. 2.13: Embroidered connections for sensor feedback (2009):

<http://www.ecouterre.com/led-equipped-climate-dress-monitors-carbon-dioxide-in-the-air/>

Fig. 2.14: Embroidered connections (2006):

www.vividiwiki.ee.virginia.edu/mediawiki/images/b/ba/Wear5.pdf

Fig. 2.15: DuPont flexible inks (2014), photograph taken at Printed Electronics Berlin

Fig. 2.16: Conductive paste on nonwoven, image from Stella newsletter 6:

www.stretchable-circuits.com/projects/healthcare/stella

Fig. 2.17: Flexible copper foil circuit: <http://www.kobakant.at/DIY/?p=1132>

Fig. 2.18: Laser cut adhesive traces (2009):

<http://infosyncratic.nl/weblog/2009/04/12/stretchy-conductive-traces/>

Fig. 2.19: BURTON jacket with printed buttons (2003):

<http://www.cbc.ca/arts/photoessay/bringthenoise/index8.html>

Fig. 2.20: Internal control pad and textile cable (2013), image taken from 'QTC in Switches, Sensors, Controls and Touch-Screens' presentation:

http://www.sid.org/Portals/sid/UKI_files/SLE%20AGM%20Presentations/Peratech.pdf.

Fig. 2.21: Sense t-shirt and sensor details: <http://www.csem.ch/site/card.asp?pld=13160>

Fig. 2.22: Under armour E39 shirt (2011):

<http://www.engadget.com/2011/02/28/under-armours-e39-performance-shirt-is-electric-video/>

Fig. 2.23: First Warning System sensor bra (2014):

<https://hpectechtrends.wordpress.com/category/6-smart-technology/page/3/>

Fig. 2.24: Nike+iPod sensor (2006):

http://usatoday30.usatoday.com/tech/products/2006-05-23-apple-nike_x.htm

Fig. 2.25: Boogio concept artwork (2015): <https://www.boogio.com/press>

Fig. 2.26: Fitbit tracker attached to bra: <https://investor.fitbit.com/press/press-kit/default.aspx>

Fig. 2.27: Shine attached to shirt (2013): <http://tekarticles.com/article/category/gadgets/>

Fig. 2.28: Nike fuelband attached to laces (2013): <https://paulspeese.wordpress.com/>

Fig. 2.29: Nike+iPod sensor position:

<http://www.instructables.com/id/Put-an-iPod-Nike%2B-sensor-in-any-running--shoe-in-o/>

Fig. 2.30: Pollution monitor (2013):

<http://directorsblog.nih.gov/2013/06/27/smart-clothes-a-wearable-air-quality-sensor/>

Fig. 2.31: Electronic finger cuff (2012): www.gizmag.com/electronic-fingertips/23760/

Fig. 2.32: Jabra sensing headphones (2014):

<http://www.cnet.com/products/jabra-sport-pulse-wireless/>

Fig. 2.33: June UV exposure bracelet:

<https://learn.adafruit.com/june-uv-sensor-bracelet-teardown/inside-the-june>

Fig. 2.34: Stick-on sensor patch (2014):

http://news.illinois.edu/news/14/0403microfluidics_JohnRogers.html

Fig. 2.35: Adhesive sensor plaster:

<http://wildcat2030.tumblr.com/post/53094817374/a-wearable-alert-to-head-injuries-in-sports>

Fig. 2.36: Proteus Biomedical Raisin system (2012):

<http://mobihealthnews.com/15820/lloyds-pharmacies-to-sell-proteus-smart-pills-sensors/>

Fig. 2.37: Sensor-enabled pill (2010):

http://www.medgadget.com/2010/08/proteus_pill_ingestion_monitoring_system_gets_eu_green_light.html

Fig. 2.38: Touch sensors on flexible foil (2014):

http://www.analog-eetimes.com/en/tactile-skin-gives-prosthetics-and-robots-a-flexible-touch.html?cmp_id=7&news_id=222906388

Fig. 2.39: LED enabled stretchable electronics:

<http://www.imec.be/ScientificReport/SR2009/HTML/1213551.html>

Fig. 2.40: Flexible silicon skin stitched onto fabric:

<http://www.ece.eng.wayne.edu/~yxu/doc/researches/Intelligent%20textiles.htm>

Fig. 2.41: Stretchable electronics (2013):

<http://fashioningtech.com/profiles/blogs/christian-dils-amp-manuel>

Fig. 2.42: Epidermal electronics (2011):

<http://www.popsoci.com/science/article/2011-08/epidermal-electronics-paste-peelable-circuitry-your-skin-just-temporary-tattoo>

Fig. 2.43: Electronic tattoo (2011): <http://www.popsoci.com/science/article/2011-08/epidermal-electronics-paste-peelable-circuitry-your-skin-just-temporary-tattoo>

Fig. 2.44: Ink-jet printed circuit on paper (2014), photograph taken at Printed Electronics Berlin

Fig. 2.45: Wax-printed paper sensor (2012): [http://www.laboratory-](http://www.laboratory-journal.com/news/scientific-news/origami-styled-sensor-technology-rapid-diagnostics)

[journal.com/news/scientific-news/origami-styled-sensor-technology-rapid-diagnostics](http://www.laboratory-journal.com/news/scientific-news/origami-styled-sensor-technology-rapid-diagnostics)

Fig. 2.46: Touch-sensitive embedded joystick:

<https://www.pinterest.com/pin/12947917652202672/>

Fig. 2.47: Touch-sensitive buttons (2007): <http://www.talk2myshirt.com/blog/archives/225>

Fig. 2.48: Mood responsive fashion (2006):

http://www.brandspankingnew.net/archive/2006/10/wear_your_heart_on_your_sleeve.html

Fig. 2.49: Mood responsive clothing (2009):

<http://fashioningtech.com/profiles/blogs/interactive-fashion-gets>

Fig. 2.50: Sensing sports bra (2014): <http://www.snewsnet.com/news/wearing-your-data-can-a-t-shirt-or-sticker-become-your-next-outdoorfitness-motivator/>

Fig. 2.51: Sensing compression shirt (2014):

<http://www.gizmag.com/ralph-lauren-polo-tech/33504/>

Fig. 2.52: Nike+Fuelband activity tracker (2012):

<http://www.coolhunting.com/tech/nike-fuelband>

Fig. 2.53: Misfit Shine activity tracker:

<https://www.indiegogo.com/projects/misfit-shine-an-elegant-wireless-activity-tracker#/story>

Fig. 2.54: Tracking and heating insole (2015):

<http://www.ohmygeek.net/2015/01/12/digitsole-plantilla-smartphone/>

Fig. 2.55: Impact sensor skullcap (2013):

<http://www.bostonmagazine.com/health/blog/2013/07/26/reebok-launches-head-monitoring-skullcap/>

Fig. 2.56: Electrozyme tattoo sensor (2014): <http://medcitynews.com/2014/09/electrozymes-metabolism-monitoring-temp-tattoos-backed-mark-cuban/>

Fig. 2.57: Sweat sensor (2015): <http://ceas.uc.edu/news-1415/sweat-spot.html>

Fig. 2.58: Zeo sleep monitor: <http://postscapes.com/zeo-sleep-manager-pro>

Fig. 2.59: The GER mood sweater: <http://sensoree.com/artifacts/ger-mood-sweater/>

Fig. 2.60: Bellabeat Leaf baby monitor (2014): <http://www.maycouponcodes.com/bellabeat-debuts-a-trio-of-health-tracking-products-for-moms-to-be-and-beyond-including-jewelry-a-monitor-and-a-smart-scale/>

Fig. 2.61: Mimo baby monitor (2014): <http://www.damngeeky.com/2014/01/10/17222/ces-2014-mimo-baby-monitor-gives-real-time-updates-infants-vital-aspects.html>

Fig. 2.62: Georgia Tech 'Smart shirt': <http://www.gtwm.gatech.edu/>

Fig. 2.63: WEALTHY project (2005):
<http://www.engadget.com/2005/04/15/wealthy-wearable-health-care-system/>

Fig. 2.64: Artificial pancreas system (original image from www.pancreum.com, image no longer available)

Fig. 2.65: Smart contact lens (2014):
<http://www.forbes.com/sites/leoking/2014/07/15/google-smart-contact-lens-focuses-on-healthcare-billions/>

Fig. 2.66: YDreams firefighter suit:
<http://www.proetex.org/final%20proetex%20learning/firefighters.htm>

Fig. 2.67: Proetex t-shirt
<http://www.ugent.be/ea/textiles/en/projects/afgelopenprojecten/Proetex.htm>

Fig. 2.68: Heat responsive fashion (2014):
<http://fashioningtech.com/profiles/blogs/alexander-wang-s-heated-activated-garments>

Fig. 2.69: Heat responsive sportswear (2014):
<http://materialicious.com/2013/06/radiate-athletic-apparel.html>

Fig. 2.70: Swine flu mask with pattern enabled warning system (2009):
<http://www.ecouterre.com/color-changing-temp-sensitive-textiles-flu-masks/>

Fig. 2.71: Environment-responsive fashion:
<http://seetheunseen.co.uk/collection-archive/air/>

Fig. 2.72: Rainwater-responsive palette: <http://www.ecouterre.com/dahea-suns-cabbage-dyed-dresses-change-color-to-indicate-rains-ph/>

Fig. 2.73: pH level test strip (2014):
<http://www.livestrong.com/article/88456-test-body-ph-levels/>

Fig. 2.74: Paper litmus test (2012):
<http://phys.org/news/2012-03-nerve-gas-litmus-airborne-chemical.html>

Fig. 2.75: Origami-inspired glucose sensor (2015):
<http://www.makoinvent.com/prototype-creators-make-origami-hiv-testers/>

Fig. 2.76: Paper based glucose sensor:
<http://gmwgroup.harvard.edu/research/index.php?page=24>

Chapter 3

Fig. 3.1: Electronic waste (a), textile waste (b) and potential future e-textile waste (c):

(a) <http://www.greenpeace.org/international/en/campaigns/detox/electronics/>

(b) <http://flowliving.com/fashion-with-a-mission/>

(c) <http://www.devicemag.com/2014/05/09/wearable-technology-gets-into-your-shirt-omsignal-makes-that-happen-for-199/>

Fig. 3.2: Misfit Shine wristband worn on leg (2014):

<http://www.lovingontherun.com/2014/02/misfit-wearables-shine-activity-tracker-review/>

Fig. 3.3: Mishit t-shirt with sensor pocket: <http://www.stuffi.fr/misfit-technical-tee-t-shirt-shine/>

Fig. 3.4: 'The Shirtulator' (a), 'Fabrications' concept wrist phone (b), iPod control integrated school blazer (c):

(a) Image taken from Dunne, L. (2010) 'Smart Clothing in Practice: Key Design Barriers to Commercialization' *Fashion Practice: The Journal of Design, Creative Process & the Fashion Industry*, 2 (1), pp. 41-66(26).

(b) <http://www.innovationintextiles.com/smart-textiles-nanotechnology/groundbreakers-that-break-the-bank/>

(c) http://www.theregister.co.uk/2008/08/15/mns_school_ipod_jacket/

Chapter 4

Fig. 4.1: Research map diagram, Pahl (2014), based on first three stages of Double Diamond (Design Council, 2005)

Fig. 4.2: 'Three strands of enquiry' diagram, Pahl (2014)

Fig. 4.3: Research methods & tools diagram, Pahl (2015) based on Gray & Malins (2004)

Fig. 4.4: Key practice-based methods timeline diagram, Pahl (2015)

Fig. 4.5: PAR methods and data generated diagram, Pahl (2015)

Chapter 5

Fig. 5.1: OneMoment natural rubber shoe (2012):

<http://www.wired.com/2012/10/one-moment-01m/>

Fig. 5.2: Liquid natural rubber latex in mould, Pahl (2013)

Fig. 5.3: Plain rubber and rubber with natural flock samples, Pahl (2013)

Fig. 5.4: Layout for simple circuit and battery-powered circuit with LED, Pahl (2013)

Fig. 5.5: Rubber and natural flock samples with touch sensor, stitched circuit and LEDs, Pahl (2013)

Fig. 5.6: Rubber and natural flock sample with touch sensor and stitched circuit and LEDs, Pahl (2013)

Fig. 5.7: Sample testing at Smart Fabrics 2013 evening reception (photograph)

Fig. 5.8: Eccrine sweat glands including the palms and forearms, Pahl (2013)

Fig. 5.9: Natural rubber substrate with embedded wool crochet, Pahl (2013)

Fig. 5.10: Liquid latex coloured with thermochromic/ food colouring pigments, Pahl (2013)

Fig. 5.11: Liquid and dried latex coloured with photochromic pigments, Pahl (2013)

Fig. 5.12: Natural rubber with food colouring and embedded natural flock, Pahl (2013)

Fig. 5.13: Bioplastic with food colouring and surface embedded hemp flock, Pahl (2013)

Fig. 5.14: Melissa thermoplastic shoe (2010):

<http://www.digoporai.com/2010/06/costela-de-adao/>

Fig. 5.15: Silicone rubber material sample, PrahI (2013)

Fig. 5.16: Silicone rubber and polyester crochet hand-worn sensor prototype, PrahI (2013)

Fig. 5.17: Silicone rubber wristband with cotton and bamboo needle-punch and embedded LED, PrahI (2013)

Fig. 5.18: Considering disassembly for devices made with heterogeneous materials, samples and sketches, PrahI (2013)

Chapter 6

Fig. 6.1: Diagram showing MATERIAL focus, PrahI (2015)

Fig. 6.2: BioCouture grown material (2010): <http://www.treehugger.com/sustainable-fashion/from-a-vat-of-green-tea-grows-gross-but-cool-green-fashion-called-biocouture-photos.html>

Fig. 6.3: Nike Flyknit technology (2014):

<http://weartesters.com/weekly-sneaker-discussion-episode-1-flyknit-vs-primeknit/>

Fig. 6.4: Puma InCycle process diagram (2013):

http://www.sustainablebrands.com/news_and_views/waste_not/puma-introduces-c2c-certified-recyclable-track-jacket-backpack-part-incycle

Fig. 6.5: Biodegradable electronics:

<http://phys.org/news/2012-09-transient-electronics-biocompatible-electronic-devices.html>

Fig. 6.6: 'Active disassembly' for mobile phones (2006):

<http://www.treehugger.com/gadgets/gadgets-that-self-destruct-active-disassembly.html>

Fig. 6.7: Design strategy for material stories: Skin-tech and Tecrochet diagram, PrahI (2013)

Fig. 6.8: Skin-tech mood board using secondary and primary research images, PrahI (2013):

(a) <http://www.hennabyholly.com/blackhenna.html>

(b) Natural flock print, PrahI (2009)

(c) <http://www.popsoci.com/science/article/2011-08/epidermal-electronics-paste-peelable-circuitry-your-skin-just-temporary-tattoo>

d) <http://thecreatorsproject.vice.com/blog/suzanne-lee-grows-her-own-biocouture-bomber-jackets>

(e) J Smith ESQ, Peek-a-Boo Magazine: POP Fall/Winter 2007 (scan)

(f) <http://web.media.mit.edu/~neri/site/projects/carpalskin/carpalskin.html>

Fig. 6.9: Selection of hand-made biological material samples, PrahI (2013)

Fig. 6.10: Selection of hand-made technical material samples, PrahI (2013)

Fig. 6.11: 'Second skin' board utilising primary and secondary images and swatches, PrahI (2013):

(a) <http://bioalloy.org/micro-be>

(b) Bioplastic sample PrahI (2013)

(c) <http://www.technovelgy.com/ct/Science-Fiction-News.asp?NewsNum=580>

(d) Thin and flexible latex and bio plastic swatches, Prah (2013)

Fig. 6.12: 'Fused Encapsulation' board, Prah (2013):

(a) <http://www.vttresearch.com/media/news/biodegradable-nappies-from-recycled-cardboard>

(b) Latex encapsulated flock sample Prah (2013),

(c) <http://www.tamicare.com/#!/cosyflex/c1gza>

(d) Natural fibre embellished latex substrates, Prah (2013)

Fig. 6.13: 'Melted layers' board, Prah (2013):

(a) Marbled colour latex sample image, Prah (2013)

(b) POP Magazine S/S 2011 (scan)

(c) www.wgsn.com (subscribers only)

(d) Colour infused latex substrates, Prah (2013)

Fig. 6.14: Tecrochet mood board using secondary research images, Prah (2013):

(a) <http://news.motorbiker.org/blogs.nsf/dx/bikini-makes-the-scooter.htm>

(b) <http://www.agamanolis.com/distancelab/projects/solar-vintage/>

(c) <http://joshsphear.com/blog/nike-flyknit>

(d) <http://www.kobakant.at/DIY/?p=1993>

(e) <http://www.gizmag.com/n12-3d-printed-bikini/18869/>

(f) Valentino S/S 2012 coated tank top magazine image (scan)

Fig. 6.15: 'Second skins' board, Prah (2013):

(a) <http://yostatus.com/nike-free-flyknit/>

(b) <http://www.knittingindustry.com/warp-knitting-crochet/nike-pro-elite-knit-seamless-breathable-and-lightweight/>

(c) Crochet bikini magazine image (scan)

(d) Various crochet swatches utilising biological and technical yarns

Fig. 6.16: 'Future yarn' board, Prah (2013):

(a) WGSN global material direction S/S 15, www.wgsn.com (subscribers only)

(b) Plastic net photograph, Prah (2013),

(c) <http://www.thisiscolossal.com/2013/03/horses-made-of-wool-thread-dipped-in-tar-and-latex-by-sandrine-pelletier/>

(d) Various crochet swatches utilising biological and technical yarns, Prah (2013).

Fig. 6.17: 'Tech coating' board, Prah (2013):

(a) <http://www.made-in-china.com/showroom/lungchar001/product-detailQoHEXzfPaeVM/China-10-G-Cotton-Yarn-Latex-Palm-Coated-Glove.html>

(b) Latex-backed crochet sample A. Prah, 2013

(c) WGSN global material direction S/S 15, www.wgsn.com (subscribers only)

(d) Various latex-coated crochet swatches utilising biological yarns, Prah (2013).

Fig. 6.18: Additional 'Skin-tech' samples, Prah (2013).

Fig. 6.19: Additional 'Tecrochet' samples, Prah (2013).

Fig. 6.20: Rubber-like wearable substrate samples overview, Prah (2014)

- Fig. 6.21:** Textile-like wearable substrate samples overview, Prah (2014)
- Fig. 6.22:** Paper-like and film-like wearable substrate samples overview, Prah (2014)
- Fig. 6.23:** Interactive workshop session (photograph)
- Fig. 6.24:** Group discussion on materials (photograph)
- Fig. 6.25:** Handling prototypes and commercially available material samples (photograph)
- Fig. 6.26:** Preferred choices for body-worn material substrates (photographs)
- Fig. 6.27:** Cardboard cellulose nonwovens, VTT Finland (2013)
<http://phys.org/news/2013-03-biodegradable-nappies-recycled-cardboard.html>
- Fig. 6.28:** Issey Miyake paper fashion (2008):
<http://dianepernet.typepad.com/diane/2008/12/rrripp-paper-fashion-exhibition-at-mudamluxembourg-until-february-2nd-.html>
- Fig. 6.29:** Denim inclusions and indigo dyed cotton rag pulp during papermaking process, Prah (2014)
- Fig. 6.30:** Recycled magazines, cotton rag and denim inclusion paper samples, Prah (2014)
- Fig. 6.31:** Thermo-chromic pigment dyed and painted cotton rag pulp and natural fibre inclusion paper, Prah (2014)
- Fig. 6.32:** Cabbage dyed cotton rag pulp and cabbage dipped cotton rag pulp and denim inclusion paper, Prah (2014)
- Fig. 6.33:** Embossed thermochromic paper and wet denim coloured paper, Prah (2014)
- Fig. 6.34:** Disposable bra material worn on forearm for 24 hours (photographs)
- Fig. 6.35:** Synthetic tattoo cover material worn on forearm for 24 hours (photographs)
- Fig. 6.36:** Frownies Kraft paper-based facial patches with thermochromic print (photographs)
- Fig. 6.37:** Frownies Kraft paper-based patches worn on forearm for 3 hours (photographs)
- Fig. 6.38:** MC10 flexible epidermal electronics (2013):
<http://www.dezeen.com/2013/03/28/biostamp-temporary-tattoo-wearable-electronic-circuits-john-rogers-mc10/>
- Fig. 6.39:** Fabrican sprayable nonwoven fabric (2010):
<http://news.softpedia.com/news/Clothes-in-a-Can-Fabrican-Comes-Out-with-Spray-On-Fabric-156696.shtml>
- Fig. 6.40:** Paper-like, rubber-like and felt-like wearable material concept, utilising secondary images, Prah (2014):
 (a) <http://www.designandpaper.com/?p=5512>
 (b) <http://fashioningtech.com/profiles/blogs/crafting-inlaid-skin-an-interview-with-andreea-mandrescu>
 (c) <http://www.myfootshop.com/metatarsal-pad-felt-1>
- Fig. 6.41:** Developed 'material' outcome and focus diagram, Prah (2015)

Chapter 7

- Fig. 7.1:** Diagram showing FORM focus as part of three-stranded investigation, Prah (2015)

Fig. 7.2: On-body activity tracker positions (2013):

<http://www.patientdriven.org/2013/12/>

Fig. 7.3: Face-worn Wearable Technology (2013):

<http://www.telegraph.co.uk/technology/google/10494231/The-places-where-Google-Glass-is-banned.html>

Fig. 7.4: initial wear testing of a Fitbit One activity tracker (photograph)

Fig. 7.5: Initial wear testing of an iPhone 5 during running (photographs)

Fig. 7.6: Internal stimuli location diagram, Prael (2013)

Fig. 7.7: Sweat sensing plaster (2014):

<http://www.geglobalresearch.com/blog/health-information-can-pore-right>

Fig. 7.8: Printed sensor (UCSD):

http://www.electronicproducts.com/Sensors_and_Transducers/Sensors/P_F_Sensors_their_future_and_challenges.aspx

Fig. 7.9: Experimental textile sensors to measure sweat pH (2009), images taken from paper: http://doras.dcu.ie/3636/1/Coyle_pervasive2009.pdf

Fig. 7.10: External stimuli location diagram, Prael (2013)

Fig. 7.11: Clarity wearable air pollution sensor (2014):

<http://thenextweb.com/insider/2014/11/06/awesome-hardware-startups-haxlr8rs-demo-day/>

Fig. 7.12: Estimote Nearable sensor (2014):

<http://www.gizmag.com/estimote-nearables/33470/>

Fig. 7.13: Reference images (Internet) for neck and back-worn accessories:

(a) <http://www.whoateallthepies.tv/kits/94296/mario-balotelli-unveils-personalised-super-mario-snood-at-man-city-training.html>

(b) <http://www.caregiverproducts.com/elasto-gel-neck-support-roll.html>

(c) <http://www.colne-osteopathy.co.uk/Kinesiotape/kinesiotapeColneosteo.html>

(d) <http://www.amazon.com/POSTURE-CONTROL-BRACE-SUPPORT-BEIGE/dp/B000Y0ACSG>

Fig. 7.14: Reference images (Internet) for underarm-worn accessories:

(a) <https://www.advantagewear.com/snapshields.html>

(b) <http://www.amazon.co.uk/Sleeve-Compression-Garment-Large-Nude/dp/B00BAVDHAI>

(c) <http://www.groupme.my/Product/5pairs-Underarm-Dress-Clothing-Sweat-Perspiration-Pads-Shield-Pay-only-RM15-instead-of-RM30/4138>

(d) http://guide.alibaba.com/shop/0760-adjustable-single-shoulder-pad-basketball-badminton-tennis-ball-outside-sport-shoulder-pad_5572152.html

Fig. 7.15: Reference images (Internet) for forearm and forearm-worn accessories:

(a) <https://plus.google.com/117959892632570569457/posts>

(b) <http://www.happyhatsandsaddlecreek.co.uk/product/cashmere-wrist-warmers/>

(c) <https://www.pinterest.com/pin/63824519692878845/>

(d) <http://www.fishpond.co.uk/c/Toys/q/tattoo+sleeves?rid=1868273935>

Fig. 7.16: Reference images (Internet) and sample image for hand-worn accessories:

- (a) <http://pamperedandpolished.co.uk/2010/10/nail-rock-designer-nail-wraps/>
- (b) Fingerless glove sample (photograph)
- (c) <http://painreliefsupports.co.uk/IMAK/IMAK-Active-Arthritis-Compression-Gloves-%28Pair%29>
- (d) <http://www.lifechilli.com/crochet-ring-patterns-and-ideas-for-beginners/>

Fig. 7.17: Reference images (Internet) and samples for foot-worn accessories:

- (a) <https://www.flickr.com/photos/35628588@N07/4143440402>
- (b) http://products.unbeatable.com/gadget_universe_th003m_latex_gloves_for_your_feet_medium_1017261221.php
- (c) Padded crochet foot accessory (photograph)
- (d) Scholl insole (photograph)

Fig. 7.18: Reference images (Internet) for head-worn accessories:

- (a) <https://www.swim-shop.com/index.php?cPath=1767>
- (b) <http://www.foska.com/ear-warmer.html>
- (c) http://www.hammacher.com/publish/74419.asp?source=google&keyword=180s+earmuffs&cm_ven=NewGate&cm_1
- (d) http://www.chicagorunnergirl.com/2011_11_01_archive.html

Fig. 7.19: Reference images (Internet) for face-worn accessories:

- (a) <http://www.pamperedprince.co.uk/2013/03/jamela-24k-gold-under-eye-masks.html>
- (b) http://makeupuniversity.blogspot.co.uk/2011_07_01_archive.html
- (c) <http://www.ebay.com/bhp/face-slimming-mask>
- (d) <http://www.sofmilitary.co.uk/shop-airsoft-protective-eyewear-and-face-masks-category%2C901>

Fig. 7.20: Reference images (Internet) for leg-worn accessories:

- (a) <http://becuo.com/nike-pro-combat-leg-sleeve>
- (b) <http://www.ebay.com/itm/Cramer-ESS-Reflective-Calf-Compression-Support-Sleeves-1-Pair-/121195821067>
- (c) <http://www.stagestruckdancewear.com/images/Womens%20DancewearLeg%20Warmers.html>

Fig. 7.21: Reference images and samples for adhesive accessories:

- (a) Kinesio sports tape pack (photograph)
- (b) <http://www.astrongmanscupoftea.com/2012/11/2012-inappropriate-or-awesomely-cool.html>
- (c) <http://www.candybeeswimwear.com/new-self-adhesive-silicone-backless-strapless-bra/>

Fig. 7.22: Head-worn sensor concept board, Prah1 (2014)

Fig. 7.23: Face-worn sensor concept board, Prah1 (2014)

Fig. 7.24: Back & neck-worn sensor concept board, Prah (2014)

Fig. 7.25: Armpit-worn sensor concept board, Prah (2014)

Fig. 7.26: Forearm-worn sensor concept board, Prah (2014)

Fig. 7.27: Palm-worn sensor concept board, Prah (2014)

Fig. 7.28: Leg-worn sensor concept board, Prah (2014)

Fig. 7.29: Foot-worn sensor concept board, Prah (2014)

Fig. 7.30: Workshop introduction (photograph)

Fig. 7.31: Workshop activity (photograph)

Fig. 7.32: Wearable sensor concepts display at workshop (photograph)

Fig. 7.33: Bought reference samples (photograph)

Fig. 7.34: Wearable sensor concepts display at user workshop (photograph)

Fig. 7.35: Wearable sensor concepts group discussion (photograph)

Fig. 7.36: Skin, body and clothing as the sensor carrier, Prah (2014):

(a) <http://www.rsc.org/chemistryworld/2012/06/electronic-skin-health-and-security-checks>

(b) <https://www.newscientist.com/article/dn22162-fingertip-tingle-enhances-a-surgeons-sense-of-touch/>

(c) <https://hpectechtrends.wordpress.com/category/6-smart-technology/page/3/>

Fig. 7.37: Developed 'form' outcome and focus diagram, Prah (2015)

Chapter 8

Fig. 8.1: Diagram showing FUNCTION focus, Prah (2015)

Fig. 8.2: Attendance confirmation of first Show & Tell meet-up in 2012 (image)

Fig. 8.3: Analogue and digital self-quantification and tracking (photograph)

Fig. 8.4: Primary/ secondary research data combined (photograph)

Fig. 8.5: Research data evaluated into key messages diagram, Prah (2013)

Fig. 8.6: QS presentation on Vimeo, screengrab from: <https://vimeo.com/68775423>

Fig. 8.7: 'Show & Tell' talk at Meetup (photograph)

Fig. 8.8: User-need diagram, Prah (2013)

Fig. 8.9: 2nd Show & Tell presentation (photograph)

Fig. 8.10: Pollution scenario 2020: Outdoor, indoor office & public spaces and indoor home, Prah (2013)

Fig. 8.11: Pollution scenario 2020 with textile-based alert and display options, Prah (2013)

Fig. 8.12: Wearable sensor response to detected environmental data, Prah (2013)

Fig. 8.13: Wearable sensor response to detected internal data, Prah (2013)

Fig. 8.14: QSer workshop, December 2013 (photograph)

Fig. 8.15: QSer workshop boards and commercial reference samples (photograph)

Fig. 8.16: Microsoft conceptual sensing bra (2015)

http://computer-guyz.blogspot.co.uk/2015_01_01_archive.html

Fig. 8.17: Cuff smart jewellery (2015)

<http://techcrunch.com/2015/01/06/cuff-raises-5-million-series-a-and-partners-with-richline-to-bring-smart-jewelry-to-the-mainstream/>

Fig. 8.18: Developed 'FUNCTION' focus diagram, Prah (2015)

Chapter 9

Fig. 9.1: Design boundaries & focus for final artefact collection diagram, Prah (2014)

Fig. 9.2: Artefact chart board, work-in-progress and close-up, Prah (2014)

Fig. 9.3: Final artefact chart diagram, Prah (2015)

Fig. 9.4: Design brief *technophile*, Prah (2014):

(a) <http://inhabitat.com/google-glass-app-helps-citi-bike-riders-get-hands-free-directions-and-info/>

(b) <http://internetmedicine.com/2012/08/31/ingestible-sensors-in-pills-approved-by-fda/>

(c) <http://www.rsc.org/chemistryworld/2012/06/electronic-skin-health-and-security-checks>

(d) <http://people.ucsc.edu/~joahanse/onlineexhibit/thirdhand/>

(e) <http://www.chrisharrison.net/index.php/Research/Skinput>

Fig. 9.5: Design brief *technoista*, Prah (2014):

(a) <http://www.thesundaytimes.co.uk/sto/style/article1415094.ece>

(b) <https://www.pinterest.com/pin/169940585911559839/>

(c) <http://solecollector.com/news/nike-launches-fuelband-se-in-japan-with-tokyo-tower-event/>

(d) <https://www.prote.in/en/feed/2014/08/yr-store-app>

(e) <http://www.engadget.com/2014/06/17/nike-fuelband-android-app/>

Fig. 9.6: Design brief *technoDIYer*, Prah (2014):

(a) <http://www.engadget.com/2010/12/14/daito-manabes-sensor-based-drum-machine-might-actually-melt-you/>

(b) <http://www.bareconductive.com/make/introducing-the-touch-board/>

(c) <https://smartcitizen.me/users>

(d) <http://www.creativeapplications.net/objects/o-system-the-future-of-personal-electronics-by-peter-krige-rca-ide/>

(e) <http://www.medgadget.com/diagnostics/page/7>

Fig. 9.7: Design brief *technosceptic*, Prah (2014):

(a) <http://qz.com/252456/what-it-feels-like-to-be-the-last-generation-to-remember-life-before-the-internet/>

(b) <http://www.reviewcentralme.com/2014/08/03/how-secure-are-your-wearable-devices/>

(c) <http://www.contemplativecomputing.org/slow-tech/>

(d) <http://lauraprins.com/technology-addiction-enmeshment/>

Fig. 9.8: Design brief *technophobe*, Prah (2014):

- (a) <http://www.dezeen.com/2013/11/28/fuseproject-designs-wearable-device-that-diagnoses-disease/>
- (b) https://en.wikipedia.org/wiki/Urine_test_strip
- (c) <http://phys.org/news/2012-03-nerve-gas-litmus-airborne-chemical.html>
- (d) <http://www.dezeen.com/2013/11/28/fuseproject-designs-wearable-device-that-diagnoses-disease/>
- (e) <http://www.floriesalnot.com/Healthy%20Pregnancy-part1.html>

Chapter 10

Fig. 10.1: *Wearable Skin* concept board, Prah (2014):

- (a) <http://web.media.mit.edu/~neri/site/projects/carpalskin/carpalskin.html>
- (b) <http://www.dezeen.com/2013/11/04/diy-cyborg-implants-body-monitoring-device-under-his-skin/>
- (c) <http://i.huffpost.com/gen/1052608/images/s-BODY-HACKING-large.jpg>
- (d) <http://hitconsultant.net/2015/03/27/google-patent-smart-contact-lens-for-diabetes/>
- (e) https://en.wikipedia.org/wiki/Skinput#/media/File:Skinput_arm_buttons.JPG

Fig. 10.2: *Wearable Skin* textile inspiration, Prah (2014):

- (a) <http://www.wired.com/2010/12/foot-stickers-the-most-minimal-sneakers-around/>
- (b) [http://www.materialecology.com/projects/details/arachne#prettyPhoto\[arachne\]/1/](http://www.materialecology.com/projects/details/arachne#prettyPhoto[arachne]/1/)
- (c) Latex paint experiment, Prah (2013)
- (d) <http://www.dezeen.com/2013/03/28/biostamp-temporary-tattoo-wearable-electronic-circuits-john-rogers-mc10/>
- (e) <http://www.ufunk.net/en/artistes/dotstolines-tattoos/>
- (f) Moulded silicone internal layer of keyboard (photograph)

Fig. 10.3: *Wearable Skin* synthetic material board 'Tech skin', Prah (2014):

- (a) <http://ralucagrada.net/Finely-Grafted-Jewellery>
- (b) <http://www.newscientist.com/article/dn22162-fingertip-tingle-enhances-a-surgeons-sense-of-touch.html>
- (c) <http://www.artaffairs.net/?Tnext=image&Titem=P01ace%20W01c3a>
- (d) Bought samples (photographs)

Fig. 10.4: *Wearable Skin* colour palette board, Prah (2014):

- (a) J Smith ESQ, Peek-a-Boo Magazine: POP Fall/Winter 2007 (scan)
- (b) Paperchase bought wrapping paper (photograph)
- (c) <http://www.trippapparel.com/2014/23986>

Fig. 10.5: *Wearable Skin* designs and mock-ups, Prah (2014)

Fig. 10.6: *Wearable Skin* designs, Prah (2014)

Fig. 10.7: *Wearable Skin* sample mock-ups, Prah (2014)

Fig. 10.8: *Wearable Skin* sensor ecosystem diagram, Prah (2014)

Fig. 10.9: *Customise/ Accessorise* concept board, Prah (2014):

- (a) <http://rawfortheoceans.g-star.com/>
- (b) <http://shop.mrkate.com/products/beautymarks-001>
- (c) <http://www.celebritydiagnosis.com/2012/08/olympic-kinesio-taping-is-fashionable-but-does-it-work/>
- (d) <http://www.thedrum.com/news/2014/05/18/adidas-new-app-lets-customers-put-instagram-pics-trainers>
- (e) <http://www.linearcanvas.com/photographoqar/nail-wraps-aztec>
- (f) <http://blog.creativeaction.co.uk/2014/04/30/julia-noni-nikes-global-campaign/>

Fig. 10.10: *Customise/ Accessorise* textile inspiration board, Prah (2014):

- (a) <http://www.textilegence.com/jeanologia-presents-greenindustrial-times/>
- (b) <http://www.mohawkconnects.com/feltandwire/2011/05/30/my-recipe-for-turning-pants-into-paper/>
- (c) Holiday photo digital print, Prah (2014)
- (d) <http://face-lace.com/shop>
- (e) Hand-made denim paper samples, Prah (2014)
- (f) Laser-etched Tyvek sample, Prah (2009)

Fig. 10.11: *Customise/ Accessorise* material board 'Tech paper', Prah (2014):

- (a) <http://www.designboom.com/design/ilvy-jacobs-graduation-collection-bags/>
- (b) <http://www.thisisjanewayne.com/news/2011/04/07/wahre-scheren-kunst-der-bh-aus-papier/paper-bra-2/>
- (c) <http://www.laboratory-journal.com/news/scientific-news/origami-styled-sensor-technology-rapid-diagnostics>
- (d) http://www.dvice.com/archives/2008/04/lunar_design_bl.php
- (e) Bought samples including Tyvek, Polyester, Evolon, Polypropylene (photographs)

Fig. 10.12: *Customise/ Accessorise* colour palette board, Prah (2014):

- (a) Sportswear International No. 232 magazine cover (scan)
- (b) Customised Chanel backpack, Elle Magazine (scan)
- (c) Recycled magazines strips for papermaking (photograph)
- (d) Various colour swatches

Fig. 10.13: *Customise/ Accessorise* designs, samples & swatches, Prah (2014)

Fig. 10.14: *Customise/ Accessorise* designs, samples & swatches, Prah (2014)

Fig. 10.15: *Customise/ Accessorise* skin and clothing attachable sticker samples, Prah (2014) and bought sample mock-ups

Fig. 10.16: *Customise/ Accessorise* sensor ecosystem diagram, Prah (2014)

Fig. 10.17: *Make(rs) &fix(ers)* concept board, Prah (2014):

- (a) <http://www.blendingpoint.com/the-b/bare-conductive-ink/>
- (b) <http://makezine.com/2007/12/23/laser-engraving-fingernail/>
- (c) <http://now-here-this.timeout.com/2013/02/25/technology-will-save-us-build-your-on-electro-synth>

(d) <http://www.designboom.com/technology/lix-3d-printing-pen-05-01-2014/>

(e) Colloidal Ink printed conductive circuits (photograph)

Fig. 10.18: *Make(rs) & fix(ers)* textile inspiration board, Prah (2014):

(a) <http://materiability.com/bioplastics-diy/>

(b) <http://www.rca.ac.uk/more/staff/matt-johnson/>

(c) <http://www.instructables.com/id/Rubber-Origami/step5/Dip-the-Crane/>

(d) Silver foil print on plastic, Prah (2011)

(e) <http://www.acs.org/content/acs/en/pressroom/newsreleases/2014/march/toward-vanishing-electronics-and-unlocking-nanomaterials-power-potential.html>

Fig. 10.19: *Make(rs) & fix(ers)* material board 'Bio film', Prah (2014):

(a) <http://www.ecouterre.com/nokias-stretchy-electronic-skin-paves-way-for-high-tech-wearables/>

(b) <http://www.andreamandrescu.com/#/fabrics/3866597>

(c) <http://news.softpedia.com/news/Clothes-in-a-Can-Fabric-Comes-Out-with-Spray-On-Fabric-156696.shtml>

(d) Hand-made swatches, Prah (2014)

Fig. 10.20: *Make(rs) & fix(ers)* colour palette board, Prah (2014):

(a) <https://www.pinterest.com/pin/74942781273912190/>

(b) <http://www.wired.com/2013/10/meet-gameboys-deformed-younger-sibling/>

(c) <http://www.hartmanfineart.net/art/game-5>

(d) Various colour swatches

Fig. 10.21: *Make(rs) & fix(ers)* designs and hand-made samples, Prah (2014)

Fig. 10.22: *Make(rs) & fix(ers)* designs and hand-made samples, Prah (2014)

Fig. 10.23: *Make(rs) & fix(ers)* hand-made rubber samples, Prah (2014)

Fig. 10.24: *Make(rs) & fix(ers)* sensor ecosystem diagram, Prah (2014)

Fig. 10.25: *Mindful Measure* concept board, Prah (2014):

(a) <http://www.dailymail.co.uk/sciencetech/article-2584437/Is-wearable-computer-300-year-old-Chinese-abacus-ring-used-Qing-Dynasty-help-traders.html>

(b) <http://www.wgsn.com/blogs/art-design-slow-tech-designs-for-digital-downtime/>

(c) <http://www.wearable.com/smart-clothing/worlds-first-interactive-heated-insoles-take-their-first-steps>

(d) <http://inhabitat.com/ohita-a-wearable-portable-air-filter-for-city-dwellers/>

Fig. 10.26: *Mindful Measure* textile inspiration board, Prah (2014):

(a) Hand-made rubber encapsulated natural fibre sample, Prah (2014)

(b) <https://blog.adafruit.com/2012/12/24/adafruit-holiday-gift-guide-2012-makey-makey/>

(c) <http://kulturpon.com/wp-content/uploads/2014/08/woolings-pleasure-320-EUR.jpeg>

(d) Tamicare rubber mesh sample (photograph)

(e) Scholl rubber/ felt bonded insole (photograph)

Fig. 10.27: *Mindful Measure* material board 'Bio-tech felt', Prah (2014):

(a) Hand-made rubber and flock sensor sample, Prah (2014)

(b) http://www.mikapoka.com/2014_08_01_archive.html

(c) <http://www.dailymail.co.uk/sciencetech/article-2509284/Victorias-Secret-talks-Tamicare-Cosyflex-3D-print-underwear.html>

(d) Bought samples (photographs)

Fig. 10.28: *Mindful Measure* colour palette board, Prah (2014):

(a) <http://newtextiles.media.mit.edu/?p=3574>

(b) <http://www.designboom.com/art/footing-a-walk-on-ceramic-installation-by-nathan-craven/>

(c) Hand-made latex and bamboo sample, Prah (2013)

Fig. 10.29: *Mindful Measure* designs and hand-made sample, Prah (2014)

Fig. 10.30: *Mindful Measure* hand-made samples, Prah (2014)

Fig. 10.31: *Mindful Measure* designs and hand-made samples, Prah (2014)

Fig. 10.32: *Mindful Measure* sensor ecosystem diagram, Prah (2014)

Fig. 10.33: *Bio Sense* concept board, Prah (2014):

(a) <http://seetheunseen.co.uk/collection-archive/air/>

(b) Red cabbage close-up (photograph)

(c) <http://trade.indiamart.com/search.mp?search=litmus+papers>

(d) <http://www.afterdrk.com/shopping-golden-gadget/>

(e) Thermochromic flock sample, Prah (2009)

Fig. 10.34: *Bio Sense* textile inspiration board, Prah (2014):

(a) <http://en.wikipedia.org/wiki/Hypercolor>

(b) Embossed paper pattern hand-made sample, Prah (2014)

(c) <http://www.ecouterre.com/dahea-suns-cabbage-dyed-dresses-change-color-to-indicate-rains-ph/>

(d) <http://www.nic.funet.fi/index/FUNET/history/mbase/en/reika.html>

(e) <http://www.philippawagner.co.uk/blog/tags/wearables/>

Fig. 10.35: *Bio Sense* material board 'Bio paper', Prah (2014):

(a) <http://bridalmakeovers.com/blog/category/bridal-portraits/>

(b) http://commons.wikimedia.org/wiki/File:1-Blue_and_red_litmus_paper.jpg

(c) <http://www.swomag.com/bea-szenfeld-and-haute-papier/#.VXnaekT8dLo>

(d) Various bought samples (photographs)

(e) Hand-made samples, Prah (2014)

Fig. 10.36: *Bio Sense* colour palette board, Prah (2014):

(a) <http://www.featureshoot.com/2013/04/a-punk-rock-approach-to-still-life-photography/>

(b) <http://mad-science.wonderhowto.com/how-to/diy-lab-equipment-make-your-own-litmus-paper-using-cabbage-juice-0134730/>

(c) https://www.flickr.com/photos/jeremy_holden/3664972454/in/faves-geninne/

(d) Various colour swatches

Fig. 10.37: *Bio Sense* designs and hand-made samples, Prah (2014)

Fig. 10.38: *Bio Sense* designs and hand-made samples, Prah (2014)

Fig. 10.39: *Bio Sense* hand-made samples and mock-ups, Prah (2014)

Fig. 10.40: *Bio Sense* sensor ecosystem diagram, PrahI (2014)

Chapter 11

Fig. 11.1: Summary of research outcomes and contributions to knowledge diagram, PrahI (2015)

Appendix A:

Wearable Technology: Issues and challenges across the lifecycle stages

This section highlights and summarises issues and challenges identified following the initial literature and contextual review in 2012, in order to provide insight and inspiration for the design and development of wearable sensor concepts as part of the research project.

1. Issues and challenges during the design & development stage

Aesthetics

Although, compared to earlier developments, which were described by Seymour (2008) as ‘...*functional but awkward to wear and look at*’, many of today’s conceptual and academic Wearable Technology developments are becoming more attractive and considered, often pushing aesthetic preconceptions and boundaries. Conceptual designs such as *Aeolia* in 2010 and Magnhild Disington’s *Future Connections* series in 2009, explore aesthetics through the creation of highly tactile material surfaces, in order to challenge existing preconceptions of wearable textile systems, which can often be described as having a hi-tech, gadget-like and masculine appearance, especially in the commercial consumer products arena, where most of the products and devices still follow a more predictable and simplistic aesthetic path.

Indeed, Dunne (2010) observed that the impact of a worn article on the identity of the wearer is often overlooked or marginalised by designers of Wearable Technology, resulting in products that are more suitable to the aesthetics and image of mobile devices. With regard to earlier developments, Lee (2005) talks about the problem of a ‘*Cyborg Aesthetic*’, unsuitable and undesirable for clothing or fashion, which in her opinion, is caused by putting computers into clothing, rather than making the fabric itself the computer. The consideration of fashion trends must be incorporated into current and future designs, if these products are to appeal and be successful with a broader audience. However, as fashion trends change more quickly than product or technology aesthetics (Dunne, 2010), this is a challenging dilemma that will need to be considered and solved by designers creatively. Chang (2005) offers further insight into this problem, pointing out that an important consideration for the successful integration of electronics into clothing fit for the

fashion industry, must be to design and market the products with the customer's lifestyle in mind, targeting a very specific end-user and market.

Interdisciplinary collaboration

Due to the complexity of the design and development of wearable electronics and textile systems, it will be vital to further develop and implement new systems of collaboration between electronics, garment and textile experts on a commercial level. Essentially, successful design and development requires the cross-industrial collaboration of very different sectors, most of which are currently not compatible with each other in terms of the design and development process, sampling and production procedures or communication and companies experienced enough both in electronics and textiles are extremely rare. In her aptly titled '*Engineers are from Mars, Fashion designers are from Venus: Bridging the gap between two opposing industries*', Chang (2005) poses the question of how to develop research into commercially successful products, when there is little evidence of communication between technology and fashion industries, in order to encourage and support vertical integration between design and engineering. To this point, Seymour (2010) believes that it is important to create specialised design and production studios like her own collaborative Fashionable Technology Studio and Lab based in Vienna, in order to encourage fruitful multidisciplinary collaboration between computing, fashion and industrial design and wireless networking and software engineering experts.

A particular issue arising from the inter-disciplinary mismatch is the successful blending of electronic components and materials. Although the ICD+ jacket produced in a Philips and Levi's collaboration failed to become a commercial success, it was seen as an interesting 'world first', giving an indication of how two existing industry experts from very different sectors could collaborate to create something innovative and new (Malmivaara, 2009). This jacket is generally not considered a genuine wearable technology innovation, as it served as a '*mere carrying platform*' (*ibid.*) for housing electronic devices and their cables in specially designed pockets. Technologies often appear to be superficially added and connected to the carrying textile, garment or accessory, a practice, which is described by Dunne (2010) as the '*grafting on*' of traditional electronic techniques onto traditional apparel construction methods. This existing practice highlights that the coming together of different industries must go much deeper to create a mutual understanding of each other's design, construction and manufacturing processes

and foster the development of a shared language. Dunne (2010) further suggests that this type of understanding can be developed through effective inter-and multidisciplinary research and development, combining the strengths and skills of both academic and industrial work in this field, thus overcoming any disciplinary obstacles that currently exist.

Although history has witnessed some successful and innovative collaboration between academia and industry, many remain at prototype stage and are never developed commercially. The Reima 'Cyberia' smart clothing for Arctic survival project presented in 2001, brought together extensive resources from science, design and technology, both from academic and industry background. Despite a development budget of approximately one million US dollars and a working prototype, achieving all required objectives (Mattila, 2001), there was never a commercial product plan for the prototype although several innovations were patented with a view to commercial application in the future. Other inter-disciplinary studios include XS Labs, a design research studio with a focus on innovation in the fields of electronic textiles and reactive garments run by Joanna Berzowska and the collaborative platform V2_, which promotes itself as an interdisciplinary hub for '*wearable technology artistic Research and Development*', bringing together individual artists as well as partners in academia and industry. To date, the truly collaborative, inter-disciplinary approach appears to be reserved for research and academic platform driven projects, while industry practice is lagging behind.

Design for user need

Designing without a clear direction or strategy addressing genuine user needs has lead to many unsuccessful products and developments in the past and it is obvious that the relationship and understanding between the designer and end-user play a key role in the success of a commercial product. Overloading products with functionality just because a technology is available, is not seen as a constructive or successful design approach and Ariyatun *et al.* (2005) observe that the gratuitous embedding of a wide range of electronic functions into a garment does not necessarily lead to matching the users' requirements, purchasing criteria and lifestyle. Thackara (2001) refers to this as Thackara's Law, explaining in simple terms that even the integration of a smart technology can not save a stupid product from being stupid, and urges designers to investigate which specific user needs any of the technologies could cater for, through carefully considered interaction design.

As more user-centred design approaches have been gaining popularity for the design and development of smart clothing, Ariyatum *et al.* (2005) point out that products appear to have become more wearable, especially when designed with a range of very specific tasks, such as health monitoring, in mind. Working with a clearly defined target user and related applications in mind, the designer has the opportunity to truly understand user needs and desires in terms of aesthetics, functionality, usability, price-points and other criteria related to the specific application. An early advocate of integrating a user-centred approach into the design process, Jane McCann has been working on improving the quality of life for the ageing population, by using a technology-enabled garment system, as part of her cross-disciplinary, collaborative research project '*Design for Ageing Well*'. McCann (2009) employs a user-needs driven design methodology, which embraces the collaborative design process with users, in order to create products that genuinely cater for the users' carefully researched and identified needs. Prototypes are developed with researchers, industry partners and older research participants and evaluated by the group at different stages throughout the duration of the project, allowing the development of prototypes that have been thoroughly tested for user friendliness, usability, reliability and robustness.

Integration and construction

Levels of technology integration vary widely across the vast field of Wearable Technology but generally it appears that there are two very different schools of thought with regard to technology integration; firstly products that are designed to utilise integrated or embedded electronic technology and secondly products that work on the principle of modularity, where all technical, electronic elements can be removed easily. Proetex (2009) describe the process of smart textile and clothing evolution as involving three gradual steps that will eventually lead to complete integration. Step one is referred to as '*Side by Side Systems*', where electronics are attached to the textile through pockets and other external elements and cables, switches and items such as LED lights are sewn into the clothing but remain removable or are safely encapsulated for washing and maintenance. '*Hybrid Systems*', refers to electronics that are permanently attached to the textile utilising embroidered patches or woven connections and are flexible and washable, and are classified as step two, while step three involves '*Complete Integration*', where electronic functions are completely integrated within in the clothing, textiles or fibres, producing truly electronic textiles.

Other useful categorisations include the division of all electronic textiles into '*Embedded electronics*', '*Textronics*' and '*Fibertronics*' (Catrysse, Pirotte and Puers, 2007), describing '*Embedded electronics*' as textiles with built-in existing electronic components, '*Textronics*' as materials where electronic components were manufactured by textile production techniques and '*Fibertronics*' as textiles with electronics integrated into the yarns. Seymour (2008) observes three degrees of body and technology integration, referring to '*Handheld*' systems such as mobile devices, '*Wearable*' systems including integration into fabric, embedded into clothing or textile substrates or contained in clothing, or '*Implanted*' systems, such as implants or tattoos, pointing out that with these latest technology developments, the body is becoming an extension for technology.

There are many advocates of both the modular and embedded approach, as the debate over advantages and disadvantages continues. Currently, there is a strong focus on developments of embedded and invisible technologies, driven by the desire to make technology disappear in order to become inherent in the material, rather than being an add-on. Even as early as the early 90's, Weiser (1991) talked about his desire for technologies that disappear and "*...weave themselves into the fabric of everyday life until they are indistinguishable from it*".

Berzowska (2004) called for the need to develop electronic textiles to eliminate the use of hard plastic, metal and silicon components and wires, in order to make wearable systems more wearable in terms of comfort and desirability, although Van Langenhove and Hertleer (2004) comment that despite the development of integrating components and wires into the textile, functional components essentially remain non-textile elements, which makes maintenance and durability issues important problems. With these issues in mind, removable concepts can be preferable, as they offer opportunities for easy wash care and maintenance, repair, and upgradeability, and could be used much more freely, unrestricted by the use of specific outfits. Bryson (2009) is a strong supporter of wearable technology as an independently carried device, pointing out the restrictions of a system linked to a specific item of clothing, such as the Burton AMP snowboarding jackets, while Kirstein *et al.* (2007), favour the use of a modular system concept in order to be able to utilise different integration methods, depending on the functionality requirements and cost of the components and further differentiate between cheap components with task-specific functionality that should be permanently integrated into a garment, and more expensive devices that should be usable with different outfits.

Stacey Burr from Textronics believes that one of the most important developments for electronic textiles will be the '*Plug and play*' concept (Tucker, 2007), meaning technology will be in modular form to enable easy, low cost integration. This approach is also supported by Seymour (2008), who feels that a modular system is essential for the housing of computer components, which need to be able to be easily exchanged or replaced due to potential changes in standards, failure or other maintenance issues.

2. Issues and challenges during the manufacturing stage

Complexity of cross-industry manufacture

As the two very different apparel and electronics industries join together to design, develop, produce and potentially maintain and dispose of Wearable Technology, key issues concerning production cycles begin to surface. Seymour (*ibid.*) highlights that the different lifecycles of clothing and technology have a significant impact on a workable integration between the two, as electronic products usually have a far longer lifespan than clothing and further points out that electronic components are usually manufactured in much higher numbers than garments, due to cost efficiency within a much longer research and development phase.

Furthermore, both industries are unfamiliar with each other's materials, production processes and technical language, while existing components from the electronics industry may simply not be compatible with material or garment construction, currently used in the apparel industry. Dunne (2010), suggest overcoming some of these issues through multi-disciplinary training, in order to encourage collaboration and enhance the degree of cooperation between these expert fields. Initiatives and commitment to developing new working practices, standards and a mutual understanding of manufacturing and end-use issues to bring these very different industries together, could therefore be an important step in realising the potential of this emerging and continuously evolving industry.

Resource consumption & depletion

Like in the realm of regular and technical clothing and textiles, non-renewable resource consumption and depletion is going to become a big concern in the production of Wearable Technologies, if not before, this will become more pressing once this field becomes commercially successful, thus supplying mass-market

products and devices. The complex number of components already necessary to produce electronic textiles and Wearable Technology is further exacerbated by the need to incorporate electronic and other highly technical, generally man-made and non-renewable components and materials. Although not specifically referring to Wearable Technology developments, Köhler and Som (2005) highlight their concern for the expected accelerated global resource depletion across material and energy consumption during the production of electronic goods for pervasive computing. In view of the current neglect for the consideration of resource consumption and depletion, design of Wearable Technology needs to start considering the development and use of renewable materials and components and the reduction of energy consumption during the manufacture of products immediately, in order to develop solutions and alternatives for a time when Wearable Technology becomes a ubiquitous commodity product.

Production hazards to workers and environment

The use of hazardous chemicals, substances and components could endanger factory workers, environment and the end-user and although to date this concern is rarely specifically investigated for the production of Wearable Technology, this concern has already been publicised in relation to the electronic consumer goods industry. Köhler (2008) already calls for a reduction of the use of toxic materials in the design and production of electronic textile and recent campaigns by Greenpeace have exposed that the use of toxic chemicals are already an issue in standard clothing.

3.3 Issues and challenges during the in-use stage

Sales & Services

As observed by Malmivaara (2009), electronics are generally sold in different shops than clothing and textiles, and are likely to rely on sales staff expertise during purchase and after-care. This poses the question as to which kind of retail outlet wearable technology should be sold in, to ensure the customer receives the best advice and service. Furthermore, and linked to the different lifecycles of electronic and textile components, warranty and customer service problems can occur as one component may deteriorate well before the other, rendering the product obsolete despite remaining 50 per cent functional. Malmivaara (*ibid.*) suggests that the manufacturer arranging the warranty of the product may address this, however,

often there are two or more manufacturers involved and ownership of responsibility may not be entirely straightforward but ideally the consumer will need clear guidance on who to turn to for warranty and disposal queries.

With regards to use and obsolescence, one of the major criticisms of modern consumer technologies is the concept of planned or 'built-in obsolescence', as rapidly changing software and technologies makes upgradeability a key concern. With the average lifespan of computers and mobile phones estimated to be around 2 years, and new, updated software being released on a continuous basis, this will have a significant impact on the lifecycle of a Wearable Technology system and needs to be considered by manufacturers. Another problem relates to compatibility of the components involved in the Wearable Technology system, as many existing products in the market are currently only compatible with products made by the same manufacturer or at most, a very limited range of other devices. For the consumer the ideal scenario would be to be able to connect to any devices they wish, ideally based on wireless technology. The lack of universal standards is also being debated by key organisations; ASTM International, a global leader in the development and delivery of international voluntary standards, is in the process of developing a roadmap of potential standards for the smart textile sector, identifying key areas where standards could support this emerging market (ASTM, 2012). Another example of standardisation leadership is Continua Health Alliance, who has more than 240 member companies around the world, and is pushing for standardisation for technologies in the healthcare market with the aim to improve the quality of personal healthcare.

Functionality

The challenge of creating appropriate interfaces is a key focus for Wearable Technology development, as existing interfaces designed for mobile devices are unlikely to be suitable for textiles and clothing. Dunne (2010) recognises that many commercial developments for wearable technology interfaces work from a 'default' starting point, which she believes are relying on utilising existing interfaces such as keyboards and screens, although these were never intended or designed for this very different user situation, where the user may be distracted or engaged in other activities at the same time. Research indicates that more intuitive and simple to use techniques should be utilised for the development of e-textile based interfaces to increase accessibility, user freedom and satisfaction with the device, and these may need to be less obvious approaches, potentially eliminating the use of traditional

buttons and screens that we are accustomed to from the use in traditional, stand-alone electronic devices.

Accuracy and reliability are further stumbling blocks for wearable devices and smart clothing and Seymour (2010) believes that Wearable Technologies have to be able to live up to the high expectations from the consumer. These include having to reliably function at all times, without the need for any maintenance that may be acceptable for computers or smartphones. Dunne (2010) further raises the issue of '*mismatched functionality*', a problem that smart garments have often been prone to in the past. Dunne's explains this mismatch as the use of functions that are either not well-suited to garment integration and could be performed much better by existing devices such as phones, or are more suited to other products such as accessories, or indeed, are too high-tech for the end benefit to the user and price the consumer is willing to pay.

Comfort

Comfort related issues are also often identified in this field; Berzowska (2004) mentions the irony of wearable computers not being very wearable at all, due to, the use of hard and heavy components unsuitable for this application. This notion of '*unwearable wearables*' is further supported by Bryson (2009), who addresses this issue in his paper '*Unwearables*' (Bryson, 2007), and describes the lack of consideration for the human form and the body's needs in the design-phase. Comfort requirements of clothing are far more complex than those of mobile devices (Dunne and Smyth, 2007) and are exacerbated when designing wearable technology for biophysical monitoring due to the necessity for the sensors to be close to the wearer's skin, in order to ensure quality and accuracy in the measurements. Dunne (2004) further points out the importance of good garment construction and structure, in order to make the wearable product acceptable to the user. She refers to Wearable Technology as a second skin that must be designed carefully as it needs to fulfil physical, psychological and social expectations. Hence, a totally new set of design, material, component, fit and construction considerations are required to create functional garments without any loss of comfort.

Power generation, storage and management

Power generation, storage and management is still one of the biggest challenges in most wearable technology applications, while advances in alternative approaches like solar, kinetic and thermoelectric power are being investigated and developed,

albeit, as yet without any considerable technology advances ready for efficient commercial application. Energy resources for Wearable Technology must be lightweight, easy to carry, long lasting, discreet and include low power consumption and rechargeable options, but as highlighted by Hurford (2009), batteries that fit this description are not commercially available yet, although several developments to improve the integration of batteries into textiles are currently being worked on.

Wash care

As electronics maintenance differs vastly from that of clothing, it is important to consider how two such different components can be merged into one product, while being cleaned and maintained efficiently, without causing any damage to the product. Dunne (2010) explains that consumers are likely to get annoyed by two sets of maintenance instructions, and while it is perfectly acceptable to charge and repair technology products and clean and maintain clothing, the consumer may consider the intersection of these instructions too tedious to deal with, deciding against the purchase of the smart garment all together. In the future, wash care issues may be possible to overcome, as various researchers and academics, such as at Nottingham University, who are currently working on Micro Electronic Textiles (MET), which truly integrate electronic into the fibre by embedding sensors into the yarn (Nottingham Trent University, 2013), are investigating and innovating new types of materials and technology integration, which are suitable for washing. Furthermore, as disposable and cheap Wearable Technology solutions are gathering momentum in the field of Medical & Healthcare innovation, and as clothes care including washing and drying has been identified as one of the most significant negative environmental impacts (Kobori, 2010), wearable devices of the future could be designed to consider alternative modes of cleaning such as airing, wiping or other clean-tech, such as water-less washing, or indeed, eliminate the need for washing altogether.

Potential health hazards and health related impacts

Although health implications resulting from the use of Wearable Technology have yet to be researched on an appropriate and in-depth level, issues around electromagnetic radiation, battery proximity to the body and potential leakage, effects of signals from wireless communication and psychological effects, should be considered by all key actors in this industry. Public concern about electromagnetic waves due to widespread use of mobile phones and related technologies has been growing, although there is no conclusive evidence at this stage and although this

potential issue is currently only a minor concern, the constant use of mobile devices and Wearable Technology linked to these, may contribute to increasing the health risks.

The physical effects on the human body relating to the proximity to batteries and electronic components also need to be further investigated. As well as having potential harmful effects on the wearer during the use phase, batteries that are thrown away can cause significant environmental problems, which may also affect the user. As many of the devices are now worn next to the skin, Köhler and Som (2005) believe that the physical contact with microelectronics can cause potential health issues such as allergic reactions or even chronic poisoning and reiterate that strategic design steps should be taken to implement suitable encapsulation technologies or eliminate harmful substances. The ubiquity of technology and mobile devices in today's world are undeniable, and while the industry is keen to promote the positive effects on society, careful consideration for effects on the user's psyche and emotional wellbeing should be discussed.

Ho and Intille (2005) further debate the potential burden of interruptions from mobile and other digital devices, outlining that despite the advantages of receiving information whenever desired, sensor-enabled mobile devices can contribute to irritability and feelings of information overload and constant interruption. They therefore recommend that designers of mobile computing interfaces should consider developing strategies to minimise the perceived burden of information and communication delivery and in line with this observation, there appears to be increasing focus on the development of such context-aware computing concepts.

Security and privacy

As the use of advanced mobile technology and pervasive monitoring, which involve the more or less unrestricted exchange of information and gathering of data, are reaching unprecedented levels due to the paradigm shift enabled by the ubiquity of the smart phone, tablets and computers, concerns about users' personal data security and privacy are growing. Despite many companies' promising the safeguarding of personal settings to ensure privacy and data protection as well as secure data storage, many experts remain sceptical on this topic. Dembosky (2011) believes that the ubiquitous use of smartphones has dramatic implications for privacy, and further points out that the access companies like Apple and Google have to data derived from phones is extremely worrying, as this data could get into

the wrong hands for commercial gain without the user's knowledge. Although these concerns are not enough to put most users off the use of any such devices and services yet, this situation could easily change if and when the first serious and mainstream breaches of data security (such as data mining, hacking or abuse) occur, or when independent research convincingly presents evidence of the significant risks and potential consequences involved.

3. Issues and challenges at the end-of-life stage

Product recycling & remanufacturing

While there hasn't been much public evidence of consideration for sustainable issues within the Smart Textiles and Wearable Technology market to date, debates on issues around the negative impact on the environment, particularly with regard to the 'End-of-life' of electronic products are slowly beginning to emerge. In his thesis, Köhler investigates the end-of-life implications of electronic textiles (2008) stating that his findings suggest the widespread application of e-textiles could result in the emergence of a new waste stream, while Timmins (2009) suggests that all electronics-based smart clothing and wearable technology products should be considered with the Waste Electrical and Electronics Equipment (WEEE) Regulations in mind. Currently this would be problematic, as clarifications on which type of smart, electronic textiles and Wearable Technology products should fall under the WEEE Directive are extremely vague and while there is no specific legislation in place, it appears that this issue is not yet considered a matter of urgency by most designers and manufacturers involved in this industry, whether academically or commercially.

Going forward, a key consideration, which is critical during the concept and design phase, will be to look at how firmly electronic components, and therefore potential contaminants, are attached or integrated into the devices and wearables and whether or how they can be removed, so technologies and systems can be designed to facilitate the easy reuse, remanufacture and recycling of obsolete items. Considering most textile and electronic parts used in these products have a very different lifespan, successful strategies to extend product lifespan and minimise negative environmental impact by ensuring suitable disassembly and reuse or recycling at end-of-life are currently extremely rare and undeveloped.

Malmivaara (2009) raises the point of manufacturer responsibilities, suggesting that manufacturers could arrange for warranty and disposal of their products themselves, although this could prove difficult as the manufacture of the items is often in collaboration between various specialist textile and electronic manufacturers. In line with end-of-life innovation in the field of regular clothing and other electronic consumer goods and devices, such as mobile phones, alternatives to recycling worth considering as part of the design process could include concepts for re-use, repair and refurbishment strategies.

Appendix B:

QSer workshop questionnaire

Participant Questionnaire



'Wearable electronic noses for health & wellbeing'

This questionnaire will enable the researcher to record some of your feedback in response to the group activities and discussions carried out as part of the workshop, as well as generate data on more general questions relevant to the design research. Your feedback will help to inform, inspire and support the design & development of new and innovative wearable electronic nose concepts.

1. About you

Male/ Female

Age:

Do you participate in any type of self-tracking, if so, what kind of tools do you use?

2. Health issues & opportunities for digital health tools

a) Before today's presentation, were you aware of the potential negative health impacts of:

Indoor pollution	<input type="checkbox"/>
Outdoor pollution	<input type="checkbox"/>
Electromagnetic Radiation (EMR)	<input type="checkbox"/>

b) Are you concerned about these potential threats to your health?

	Indoor pollution	Outdoor pollution	Electromagnetic Radiation
Yes	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>
No	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>
Don't know	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>

Any comments:

c) Have you ever purchased and used devices, apps or other tools to protect yourself from indoor/ outdoor pollution or electromagnetic radiation. If so, which ones?

d) Before today's presentation, were you aware of the term 'Preventative Lifestyle' and it's potential positive impact on your own health & wellbeing as well as the reduction of the growing financial burden on global healthcare systems?

Yes ☐
No ☐

e) Have you personally taken any steps to lead a more 'Preventative Lifestyle', i.e. improve your quality of life and health & wellbeing in order to reduce future illness and disease. If so, what did they involve?

3. Use & wear of digital health tools

a) Before today's presentation, were you aware of any specific 'digital health tools' you could utilise to contribute to a 'Preventative Lifestyle', i.e. encourage you to adapt to a healthier lifestyle and improve your health & wellbeing, if so, which ones?

b) Based on the importance of the user taking control of their own health as part of a 'Preventative Lifestyle' approach, would you consider wearing an electronic nose device (i.e. accessory or clothing) in order to be alerted to and eliminate any potential danger to your health from indoor/ outdoor pollution or Electromagnetic Radiation?

	Indoor/ outdoor pollution	EMR
Yes	<input type="checkbox"/>	<input type="checkbox"/>
No	<input type="checkbox"/>	<input type="checkbox"/>

c) As part of a 'Preventative Lifestyle' strategy, would you consider wearing an e-nose device (i.e. accessory or clothing) capable of early detection of potential illness/ disease in response to VOCs detected from specific locations on your skin, so you could take appropriate action?

Yes ☐
No ☐

d) In order to consider wearing such a device, would you prefer it to be invisible to others or would you be happy to wear it 'on display' if you liked it's appearance/ look?

	Pollution sensor	EMR sensor	Diagnostic sensor
Invisible to others	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>
On display	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>
Don't mind	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>

4. Alert & feedback options

a) Would you prefer to receive any alerts to high levels of indoor/ outdoor pollution through the wearable device itself (i.e colour or pattern change, sound or light), your smartphone or both?

	Wearable device	Smartphone
Visibly* worn sensor device	<input type="checkbox"/>	<input type="checkbox"/>
Invisibly** worn sensor device	<input type="checkbox"/>	<input type="checkbox"/>

b) Would you prefer to receive any alerts to high levels of Electromagnetic Radiation through the wearable device itself (i.e colour or pattern change, sound or light), your smartphone or both?

	Wearable device	Smartphone
Visibly* worn sensor device	<input type="checkbox"/>	<input type="checkbox"/>
Invisibly** worn sensor device	<input type="checkbox"/>	<input type="checkbox"/>

c) Would you prefer to receive any alerts to potential issues with your health detected from your skin through the wearable device itself (i.e. colour or pattern change, sound or light), your smartphone or both?

	Wearable device	Smartphone
Visibly* worn diagnostic sensor	<input type="checkbox"/>	<input type="checkbox"/>
Invisibly** worn diagnostic sensor	<input type="checkbox"/>	<input type="checkbox"/>

* Visible to user and others

** Visible to user only

5. User Action

a) If you were alerted to dangerous levels of indoor/ outdoor pollution or Electromagnetic Radiation by your wearable sensor and/ or smartphone, would you be prepared to remove yourself from the dangerous situation in order to protect your health?

	Indoor/ outdoor pollution	Electromagnetic Radiation
Yes	<input type="checkbox"/>	<input type="checkbox"/>
No	<input type="checkbox"/>	<input type="checkbox"/>

b) Do you feel it would be beneficial to combine pollution/ EMR data received from your personal wearable sensor with additional data from sensors placed in the environment (i.e. home, office, public places, streets) in order to encourage and justify appropriate action?

Yes, this would help me to make an informed decision	<input type="checkbox"/>
No, I would be happy to take action based on my personal data	<input type="checkbox"/>

c) If your wearable sensor and/ or smartphone alerted you to potential issues regarding your health, it is likely that you would need assistance in interpreting the data to decide on a course of action. How do you envisage this process, i.e. further tools, services or healthcare professionals needed?

6. Do you have any additional comments or personal views regarding the use of wearable electronic nose devices to improve your health & wellbeing or anything else we have discussed today ?

Thank you very much for your invaluable participation today and any feedback given during previous Quantified Self meetups.

Appendix C:

User workshop questionnaire

Participant workshop questionnaire

1. About you

Name:

Age:

Profession:

2. Potential health impacts & opportunities for wearable electronic nose sensors

a) Before today's presentation, were you aware of the potential negative health impacts of:

Indoor pollution	<input type="checkbox"/>
Outdoor pollution	<input type="checkbox"/>
Electromagnetic Radiation (EMR)	<input type="checkbox"/>

b) Are you concerned about these potential threats to your health?

	Indoor pollution	Outdoor pollution	Electromagnetic Radiation
Yes	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>
No	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>
Don't know	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>

c) In general, would you consider wearing a:

	Diagnostic sensor	Pollution sensor	EMR sensor
Yes	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>
No	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>
Not sure	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>

d) If so, why would you want to wear these sensors (e.g. protection from pollution/ EMR for yourself and others, early knowledge of health issues, so preventative steps can be taken, contribute to research and government action through providing environmental data, or any other reasons)

e) If not, why would you not want to wear these types of sensors, what are your main concerns?

3. Interactive session

There are eight, **on-body location specific** wearable e-nose sensor concepts including head, face, back & neck, armpits, forearms, palms, legs and feet.

Having spent time looking at each concept board, please answer the following questions:

- a) Which of the wearable e-nose sensor concepts presented today would you *most* like to wear as part of a regular (*i.e. daily, weekly, monthly*) routine in the mid-term future (5-10 years)?

On-body location:

Concept name(s):

Why do you like this concept?

Do you have any other suggestions or thoughts on this concept?

- b) Which of the wearable e-nose sensor concepts presented today would you *least* like to wear as part of a regular (*i.e. daily, weekly, monthly*) routine in the mid-term future (5-10 years)?

On-body location:

Concept name(s):

Why don't you like this concept?

- c) If you could have your own e-nose sensor designed to suit your personality and lifestyle, what would you want it to be able to 'smell' (*i.e. detect, monitor and analyse*) and why?

Thank you very much for your participation and feedback today!

Appendix D:

The digital storage device contains additional visual documentation of the user type concepts (chapter 9) and wearable sensor collections (chapter 10). To view the original boards, sketches and samples please contact the author.